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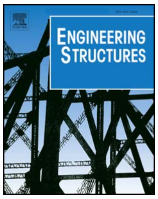

Numerical simulations to improve the use of under sleeper pads at transition zones to railway bridges

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ABSTRACT

Transition zones to bridges and other structures are critical locations in railway tracks that frequently evidence poor long-term performance. Under sleeper pads (USPs) are reported to reduce ballast degradation and control the vertical stiffness of the track, which suggests that USPs can contribute to mitigating the frequent negative effects associated with transitions zones. Aiming at understanding in greater depth the influence of USPs on the dynamic behaviour of transition zones and at improving the design of such railway structures, the authors have developed an extensive experimental and numerical study. 3-D FEM models using state-of-the-art numerical approaches were successfully calibrated and validated using experimental measurements. Simulations supported previous findings, highlighting the potential benefit of USPs and pointing to the need to careful designing of the resilient properties of USPs and their arrangement along transition zones, so as to avoid introducing abrupt variations in track vertical stiffness.

1. Introduction

Railway tracks at transition zones to bridges and other structures undergo faster degradation rates that negatively affect the railway, in terms of additional maintenance costs, longer possession times and delays, lower passenger comfort, and, ultimately, increased derailment risk [18,29,32,37,45].

Some authors argue that track resilient elements (i.e. rail pads, under sleeper pads, ballast mats) can play an important role in smoothing the sudden change in the track's vertical stiffness at these and other locations, thus contributing to mitigate the above negative effects [16,22,14,44]. Regarding the use of under sleeper pads (USP), while some studies point to its effective contribution to improve the track performance in general, others are inconclusive whether USP do actually contribute to the reduction of the track degradation. For example, recent laboratory works using reduced physical models [7] and experimental studies on the performance of railway switches and crossings [28] highlight the benefit of using USP. On the other hand, another recent study by the Norwegian National Rail Administration, on a stretch of the heavy haul Ofoten Line with 567 sleepers with USP (allowing maximum axle loads of 30 tons), showed no clear evidences of the benefit of USP after 100 MGT [27].

Regarding the application of USP at transition zones to bridges and other structures, the available literature is somewhat scarce. It is limited to few experimental [30] and numerical studies [22,14], including earlier works by the authors [3,34]. In those two previous works, the authors focused on filling the gap between numerical and field approaches to study the influence of USP on the dynamic behaviour of the train-track system. The works included extensive experimental field works, to characterise the track dynamics and measure its response under passing trains, and numerical studies using plain-strain 2-D FEM models, calibrated and validated with the field measurements. A transition zone to an underpass was used as case study and it was highlighted the benefit of USP to the performance of the transition zone if its resiliency is adequately designed to avoid introducing abrupt stiffness variations.

Following past experience, herein the authors aim at understanding in greater depth the influence of under sleeper pads on the dynamic behaviour of transition zones to bridges and at analysing the design of such structures in more detail. To that aim, the authors selected a different and more complex transition zone in the same railway line, where two types of USP (with different resilient properties) had been installed during construction to promote a smoother track stiffness transition, and carried out new experimental field works on that structure. Following previous studies [3], there was some concern that the inclusion of the USPs could introduce unwanted abrupt variations in

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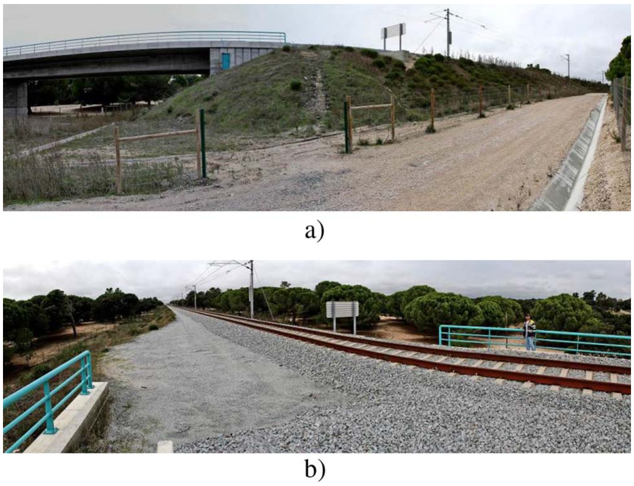
a)

b)

Fig. 1. Panoramic views of the transition from its side (a) and on the track (b).

the track vertical stiffness. Therefore, measurements were carried out to assess the behaviour of the transition zone, which were then used to calibrate and validate more advanced three-dimensional FEM models, using a cutting-edge modelling approach to study transition zones [47,48]. This numerical approach not only adequately simulates the dynamics of the vehicle, track and substructure systems, takes into account the train-track interaction and the sleeper-ballast interaction, but also allows for the consideration of irregular longitudinal level profiles of both rails independently. Only with this more complex and realistic numerical approach, together with experimental validation, is it possible to accurately assess the dynamic behaviour of transition zones with under sleeper pads, perform further simulations with confidence and look in more detail into the design process.

2. Description of the transition zone case study

The present case study is the transition zone at the north approach to São Martinho's viaduct (Fig. 1), located on the Portuguese South Main Line. The deck of the viaduct is a pre-stressed reinforced concrete structure with multiple spans of 28.4 m. The last span rests on an open abutment in reinforced concrete, founded on eight 15 m-deep piles. The stretch of the line was opened in late 2010, allowing mixed traffic, with maximum axle loads of 250 kN and maximum speed of 220 km/h for the Portuguese tilting passenger trains – the *Alfa Pendular*. It comprises a single track with Iberian gauge (1.668 m) using continuously welded UIC60E1 rails, 2.6 m long monoblock concrete sleepers (spaced at 0.6 m), a Vossloh W14 fastening system with elastomeric rail pads Zw700/148/165 (static stiffness of 50–70 kN/mm, measured under a load between 18 and 68 kN, as provided by the manufacturer).

Fig. 2 depicts the general characteristics of the track on embankment, denoting the thickness of the track layers, e, and the respective minimum degree of compaction, Dc (regarding the Optimum Modified Proctor reference value, OPM), and the minimum deformation modulus at the 2nd cycle of the plate load test, EV_2. On the viaduct, the ballast layer of the track rested directly on the concrete deck.

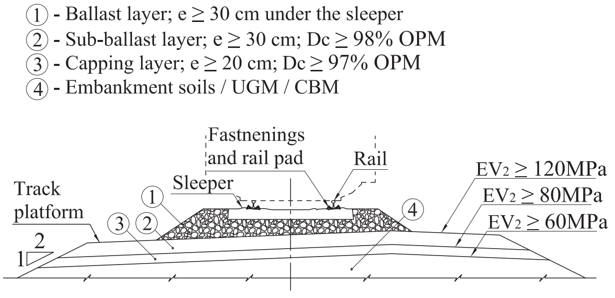

Fig. 2. Track cross section at the approach to the viaduct (after [35]).

The natural foundation of the transition zone consists mostly of monogranular fine-grained sands that provide good foundation conditions to the track substructure. The transition zone includes a backfill, about 7 m high, that was constructed using materials with better performance (higher stiffness and lower plastic deformation) than the embankment soils [36]. The backfill comprises two zones, forming a wedge-shape with the geometry depicted in Fig. 3. The first zone is located behind the abutment and comprises layers of cement bound mixture (CBM), with binder content (BC) of 5%. The average degree of compaction *in situ* was Dc = 100%, of the Optimum Modified Proctor reference value (OPM). The next zone is located between the CBM and the normal embankment. It comprises unbound granular material (UGM): a well graded crushed limestone aggregate with min./max. particle sizes of 0/31.5 mm, placed with average Dc = 99% OPM. Fig. 3 also depicts aspects of the track instrumentation, which will be addressed in subsequent sections of the manuscript.

A total of 84 sleepers with USPs were installed at this transition zone using two types of USP: (i) USP type I, 7 mm thick, with declared dynamic bedding modulus [12], $C_{dyn} = 130\ \text{MN/m}^3$ and (ii) USP type II, 10 mm thick, with $C_{dyn} = 120\ \text{MN/m}^3$. Two contiguous segments of track with USP were formed, as depicted in Fig. 3: segment (i) 50 sleepers with type II USP installed mostly on the viaduct and only 9 sleepers on the backfill; segment (ii) 34 sleepers with type I USP installed on the backfill. During the construction of the line, the USP were glued to the underside of the sleepers before being placed *in situ*. A resting period of 12 h was considered to assure a proper adhesion to the concrete sleeper.

The authors previously carried out a laboratory characterization using cyclic load triaxial tests to assess the resilient and permanent deformation behaviour of the geomaterials applied in the backfill (subballast, capping, UGM and CBM), among other more conventional tests [19,36]. The results revealed that the geomaterials were adequate for the track substructure, in terms of their physical and mechanical characteristics. The construction of the backfill followed the design requirements.

3. Track characterisation and monitoring

The authors carried out field measurements to analyse the response of the track along the transition zone when the trains passed by. It was possible to record about 40 trains, including the Alfa Pendular running at about 220 km/h and freight trains with double locomotives at about 110 km/h (Fig. 4).

The monitoring comprised various types of transducers connected to a single acquisition system, similar to that described in Paixão et al. [35] and Paixão et al. [34]. The different measuring systems were previously calibrated in the laboratory or in field tests. The following measurements were performed (at the sections depicted in Fig. 3) with an acquisition frequency rate of 2048 Hz: (i) shear deformations of the rail web, using strain gauges (resistance: 350 Ω; gauge factor: 2.0; welded to each side of the web and connected in a full Wheatstone bridge) to calculate the dynamic wheel loads (Fig. 5a); (ii) rail vertical displacements at sections 1–5, using five contactless systems that comprise a LASER (wavelength: 635 nm; power: 6 mW), mounted away from the track (Fig. 5b) and a Position Sensitive Detector (PSD) (range: ± 6 mm) (Fig. 5c); (iii) rail-sleeper vertical relative displacement, using a LVDT (range: ± 2.5 mm; sensitivity: 2 V/mm) (Fig. 5d); (iv) vertical accelerations of the sleepers, using 1D micro electro-mechanical system (MEMS) (range: ± 18 g; sensitivity: 100 mV/g) (Fig. 5e) and 1D piezoelectric accelerometers (range: ± 50 g; sensitivity: 100 mV/g) (Fig. 5f).

The positioning of the five LASER-based transducers was meant to cover the most representative and different support conditions found along the transition zone (hence different levels of track vertical