Analysis of the performance of a ballasted track in a transition zone

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Abstract. The transition zones are characterized by an abrupt change in track support stiffness, which increases dynamic wheel loads and leads to the acceleration of differential settlement and track degradation. Inefficient performance of the transition zones is a major concern of the Railway Infrastructures Managers since the degradation of the track in these areas is the cause of the generation of noise, vibration, poor ride comfort, higher risks of derailment, and a decrease of the train speed. Since the performance of the ballasted track decreases significantly in a transition zone, this work aims to study its short and long-term behaviour with a focus on a transition between a ballasted and slab track. The analysis uses a hybrid methodology, combining an iterative procedure between a 3D finite element modelling with empirical settlement equations. The FEM is capable of simulating train-track interaction. At each iteration, the track-ground stress fields are calculated using a 3D model. The stress results are the main inputs of an empirical equation capable of computing settlement across the transition. The model is used to analyse settlement and stresses for a transition zone case study, which is crucial to understand the response of the ballasted track in such areas.

Keywords: ballasted track, transition zone, short-term behaviour, long-term behaviour

1 Introduction

Transition zones are characterized by an abrupt change in the track stiffness and the development of differential settlements, which can lead to the formation of bumps and dips. These phenomena may cause passenger discomfort, compromise circulation safety, and increase maintenance costs (Frohling, Scheffel [1], Hunt [2] and Nicks [3]).

The track degradation in the transition zones begins with a sudden change in support stiffness, resulting in an increase in dynamic wheel load and consequent track geometry degradation (Dahlberg [4], Zhang, Zhang [5], Ferreira and López-Pita [6] and Asghari, Sotoudeh [7]). The differential settlements contribute to the excitation of the train components such as wheels, bogies, and car bodies, impacting the dynamic amplification of the vertical train-track interaction force.

Track geometry degradation can cause excessive noise, vibrations, poor ride comfort, and a higher risk of derailment (Paixão, Fortunato [8]). In ballasted tracks, these issues may lead to the appearance of hanging sleepers, permanent rail deformations, and ballast penetration into the subgrade. For slab tracks, similar problems can manifest as cracks in the concrete slab e/or concrete sleepers. According to the literature, this process can be considered a self-perpetuating cycle, where differential settlements lead to dynamic load amplification, resulting in increased settlements (Banimahd, Woodward [9]).

Railway transition zones can occur in various situations. In this study, a transition between a ballasted and slab track is analysed in detail. Due to the increasing popularity of the slab tracks, the number of areas with this type of transition has also risen. Shahraki, Warnakulasooriya [10], Shahraki and Witt [11] and Wang and Markine [12] studied this type of transition. However, this study goes further by incorporating the short and long-term performance of the ballasted track in a transition zone through a hybrid methodology that combines a 3D model and the implementation of an empirical permanent deformation model. This approach allows the simulation of the development of permanent deformation based on stress levels.

The objective of this work is to analyse the performance of a ballasted-slab track transition zone, with particular focus on the ballasted side due to the expected higher accelerations, deformations, and stress levels in the ballasted track. Indeed, the ballasted track is also potentially subject to higher permanent deformations compared to the slab track. Therefore, it is possible to anticipate that the ballasted track will exhibit poor long-term performance at the transition zone. The development of numerical studies allows for a better understanding of this problem. The developed approach uses a 3D FEM (finite element method) modelling approach developed in ANSYS and the permanent deformation is processed in MATLAB.

2 Numerical modelling: case study

This analysis aims to investigate the amplification of the dynamic effects resulting from the passage of an iron train, considering a variation in the stiffness support between two types of track structures: ballasted track and slab track. An illustrative example of this situation is provided in Figure 1. In this scenario, the slab track exhibits higher stiffness when compared to the ballasted track.

Figure 1 - Ballasted-slab track transition zone

The ballasted track comprises several components, including rails, railpads, sleepers, ballast, sub-ballast, soil layer 1 and soil layer 2, as depicted in Figure 2. The material parameters for this study are based on MASW (Multi-surface analysis of surface waves) results obtained from the IN2TRACK3 European Project and a demonstrator in Sweden (Nasrollahi, Dijkstra [13]). The material properties are presented in Table 1.The total length of the model is close to 48 m (28.8 m for the ballasted track and 19 m for the slab track).

Regarding the boundaries, viscous dampers (Lysmer and Kuhlemeyer [14]) were adopted to attenuate the waves that impinge the vertical boundaries. This approach has proven successful in previous works (Ramos, Gomes Correia [15] and Ramos, Calçada [16]). Additionally, fixed supports were implemented at the bottom of the soil layer 2.

All the materials were modelled with solid elements with 8 nodes. Moreover, contact elements were employed to simulate the interaction between the vehicle and the track.

The modelling takes into consideration the symmetric conditions of the problem. For the dynamic analysis, the Newmark-Raphson method was employed.

In this study, the train was simulated using a simplified approach that includes the bogies, primary suspension, mass and axle of the wheelset, and *Hertzian* stiffness. The boogies were modelled as a very stiff beam with distributed mass, while the primary suspensions were represented by a set of spring and damper elements. The wheelset was modelled as a concentrated mass and a spring with a stiffness based on *Hertzian* theory. This level of simplification was deemed sufficient since the excitation frequencies of the dynamic analysis fell within the average range of frequencies (Nielsen, Lundén [17]).

The analysis was performed considering the passage of two bogies of the iron train, operating at a speed of 60 km/h, with an axle load of approximately 30 tons.

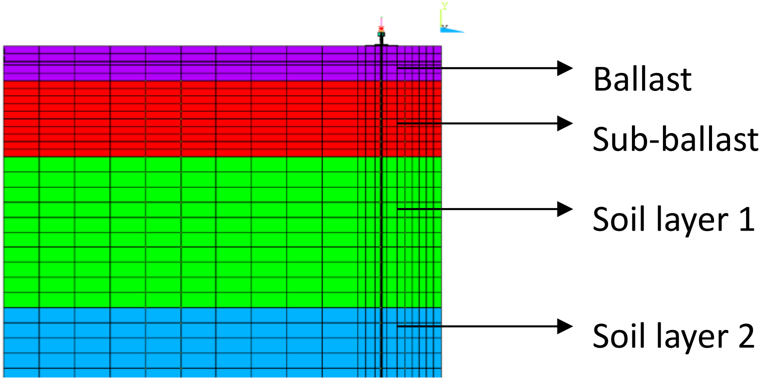

Figure 2 – Cross-section of the ballasted track

Table 1 – Materials properties

Element	E (MPa)	ν	ρ (kg/m3)	α	β
Rail	200×10^3	0.30	7850	-	-
Railpad	9.77×10^{-2}	0.00	1200	3.06	7.76×10^{-5}
Sleeper	38×10^3	0.15	2500	-	-
Ballast	67.5	0.20	1800	1.84	4.66×10^{-5}
Sub-ballast	161.7	0.30	2100	1.84	4.66×10^{-5}
Soil layer 1	472.4	0.25	2100	1.84	4.66×10^{-5}
Soil layer 2	800	0.25	2100	1.84	4.66×10^{-5}

3 Results

3.1 Short-term behaviour

The short-term performance of the ballasted track was thoroughly analysed, particularly at the transition zone, where the position x=0 m corresponds to the exact position of the transition. Figure 3 and Figure 4 illustrate the maximum displacements at the middle of the ballast and top of the concrete slab and the maximum displacement of the sub-ballast (top), respectively.

The results regarding the ballast and the concrete slab indicate that displacements decrease from the ballasted to the slab track. However, just before the transition, there is a significant increment in the displacements (the displacements double). After the transition, the displacements decrease, and the slab track exhibits a normal behaviour. It is crucial to consider this significant increase in the displacements during the design phase, primarily due to differential settlements but also because the ballast and elements at this position experience higher stresses, leading to important issues such as the hanging sleepers. Additionally, it is also important to mention that the variation of the displacements at the ballast side is due to the presence of the sleepers (periodic variation), while on the slab side, it is due to the blocks that also display a periodic geometry.

The results at the sub-ballast layer also exhibit this tendency, with a notable increase in displacement just before the transition.

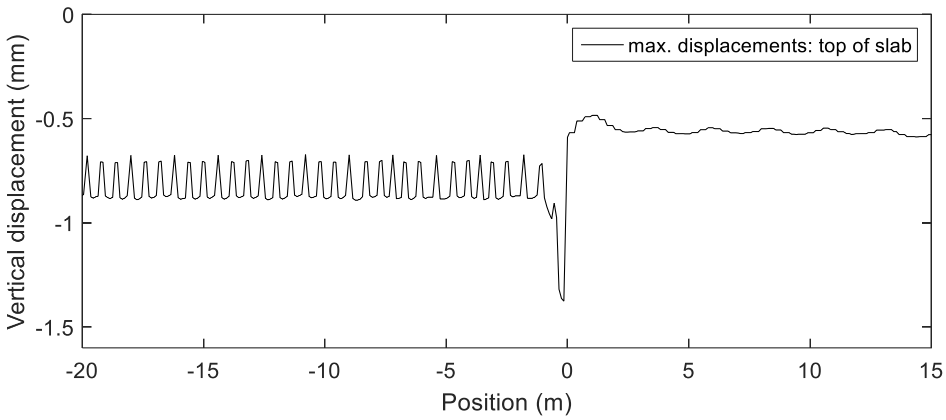

Figure 3 - Maximum displacement on the top of the slab and middle of the ballast

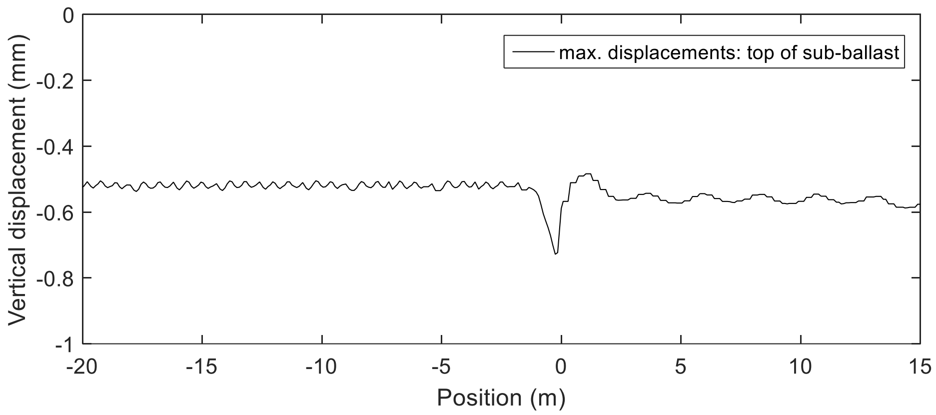

Figure 4 - Maximum displacement on the top of the sub-ballast

Regarding the short-term analysis, the stresses induced on the geomaterials were also obtained meticulously. Figure 5 illustrates the maximum stresses on the top of the sub-ballast. Similar to the displacement results, there is a significant increase in the vertical stresses immediately before the transition zone. The stresses on the sub-ballast almost doubled.

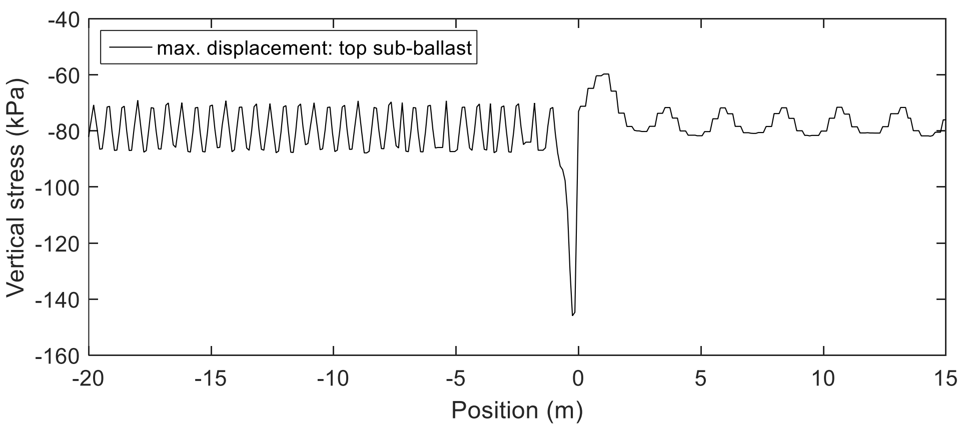

Figure 5 - Maximum stress on top of sub-ballast

3.2 Long-term behaviour

The long-term performance of railway structures, especially the ballasted track, heavily relies on the cyclic behaviour of the geomaterials. Therefore, it is crucial to select models that accurately simulate the dynamic behaviour of the track (Ramos, Gomes Correia [18] and Gomes Correia and Ramos [19]). Despite this importance, the incorporation of these results and deformation laws in complete models of the track remains an unexplored area.

The developed methodology allows for the simulation of permanent deformation in the track and can be applied regardless of the type of model or permanent deformation models used. In this study, the evolution of the permanent deformation was only considered in the sub-ballast, soil layer 1 and soil layer 2 as these elements are integral to both structures (ballasted and slab tracks). It is important to note that with the addition of the ballast, it is expected an increase in permanent deformation on the ballasted side. To conduct this analysis, the model developed by Chen, Chen [20] was applied:

$$\varepsilon_1^p(N) = \varepsilon_1^{p0}[1 - e^{-BN}]\left(\frac{\sqrt{p_{am}{}^2+q_{am}{}^2}}{p_a}\right)^a \cdot \frac{1}{m\left(1+\frac{p_{ini}}{p_{am}}\right)+\frac{s}{p_{am}}-\frac{(q_{ini}+q_{am})}{p_{am}}} \quad (1)$$

Where p_{am} and q_{am} are the amplitude of the mean and deviatoric stresses submitted by the train loadings. The parameters m and s are defined by the yielding criterion $q=s+mp$, and p_{ini} and q_{ini} represent the mean and deviatoric stresses in the material's initial state. The constants ε_1^{po}, B and a are the material-specific parameters.

By analysing the expression (1), it is possible to conclude that this model is easy to implement numerically and very complete since includes the influence of the initial stress state, the yielding criterion, and the stress caused by the passage of the train as demonstrated by Ramos, Gomes Correia [21].

The methodology relies on both the number of load cycles and the stress levels induced by the train's passage. Stress levels were derived from a 3D model of the transition and the dynamic analysis, resulting in an iterative process between the software ANSYS and MATLAB. In ANSYS, the vehicle and track numerical models are created, and data processing is performed. The stress results are then exported to MATLAB, where the permanent deformation is obtained using the selected empirical permanent deformation model (expression 1). Cohesion and friction angle values were obtained through empirical correlations between V_s, G and ϕ.

For this study, a single longitudinal section was selected along the rail alignment, as shown in Figure 6. Therefore, the cumulative permanent deformation was calculated taking into account the contributions from the sub-ballast, soil layer 1, and soil layer 2 of both systems, as depicted in Figure 7.

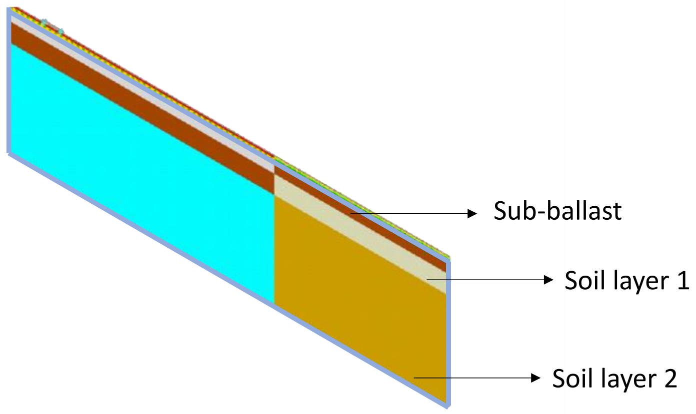

Figure 6 – Longitudinal section

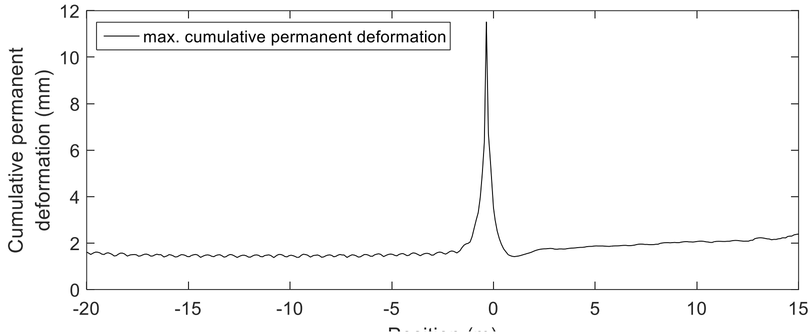

Figure 7 - Maximum cumulative permanent deformation induced in sub-ballast, soil layer 1 and soil layer 2

The results displayed in Figure 7 reveal a significant noteworthy surge in cumulative permanent deformation just before the transition. This increase is approximately six times greater compared to the permanent deformation observed in the ballasted and slab tracks farther away from the transition. The findings highlight the critical importance of addressing this specific region (position -2<x<0) to prevent potential issues such as hanging sleepers and an increase of the inertia forces and, consequently, an adverse impact on the train-track interaction.

4 Conclusions

This study offers a comprehensive analysis of the performance of a ballasted track within a ballasted-slab transition zone. The methodology employed here is noteworthy for its hybrid approach, combining a dynamic analysis developed in ANSYS to assess short-term behaviour and an empirical permanent deformation model implanted in MATLAB to evaluate the long-term behaviour. This combination allows for a holistic understanding of the ballasted track's behaviour in a transition zone.

The results demonstrate that the ballasted track presents a normal behaviour within the range of x<-2 (far from the transition) with minimal displacements and stresses induced in elements of the track. However, a significant increase in displacements and stresses is observed in certain track elements within the ballasted track close to the transition zone. These outcomes also impact the cumulative permanent deformation in the sub-ballast, soil layer 1 and soil layer 2, which are elements common to both ballasted and slab tracks. Despite this increase, and considering the properties of the materials, the obtained maximum cumulative permanent deformation value (12 mm) remains below the allowable limits.

Given the significant deformation at position 2<x<0, it is advisable to implement targeted measures to mitigate potential adverse effects. Strategies such as reinforcing the track structure and implementing enhanced maintenance practices in this critical area can help safeguard the integrity and stability of the track system. By adopting these preventive actions, safe and efficient train operations can be ensured throughout the transition zone. The findings of this study provide valuable insights for optimizing the performance and longevity of ballasted tracks in similar transition zones.

Acknowledgements. This work was partially carried out under the framework of In2Track2, a research project of Shift2Rail. This work was also partly financed by FCT / MCTES through national funds (PIDDAC) under the R&D Unit Institute for Sustainability and Innovation in Structural Engineering (ISISE), under reference UIDB / 04029/2020. It has been also financially supported by national funds through FCT – Foundation for Science and Technology, under grant agreement [PD/BD/127814/ 2016] attributed to Ana Ramos. Additionally, it was financially supported by: Base Funding – UIDB/04708/2020 of the CONSTRUCT – Instituto de I&D em Estruturas e Construções– funded by national funds through the FCT/MCTES (PIDDAC). The authors also acknowledge the EU research project IN2ZONE.

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