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DOI
10.4203/ccc.1.19.1

Publication date
2023

Document Version
Final published version

Published in
Proceedings of The Fifth International Conference on Railway Technology: Research, Development and Maintenance

The Fifth International Conference on Railway Technology
RAILWAYS 2022
22–25 August 2022
Montpellier, France

Proceedings of the Fifth International Conference on
Railway Technology:
Research, Development and Maintenance
Edited by J. Pombo
Civil-Comp Conferences, Volume 1, Paper 19.1
Civil-Comp Press, Edinburgh, United Kingdom, 2022, doi: 10.4203/ccc.1.19.1

Comparative analysis of the dynamic amplifications due to inhomogeneities at railway transition zones

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Abstract

Transition zones in railway tracks experience strong amplification of stress and strain fields due to the passage of train over inhomogeneity. The inhomogeneity in these zones can be attributed to changes in mechanical properties of material along the longitudinal direction of the track, and to displacement/traction discontinuities at interfaces leading to an amplified response in railway transition zones (TZ) with respect to the open tracks. In this paper, different kinds of inhomogeneities are considered in isolation and in combination to study the effects on railway track components in transition zone. The first type of inhomogeneity considered is non-uniformity of materials at various levels of the track along the longitudinal direction. The second type of inhomogeneity that will be considered arises from displacement and traction discontinuities at the interface of soil and structure and at the interface of sleepers and ballast (hanging sleepers). The results provide necessary insight for the design of effective mitigation measures to prevent the amplified response in railway TZ.

Keywords: railway transition zones, finite element analysis, track components, stress amplification.

1 Introduction

Over the years, several studies [1-6] have suggested that strong amplifications in stress and strain fields can be induced by moving axles of a train over an inhomogeneity along the longitudinal direction of a railway track. The inhomogeneities are inherent characteristic of the railway transition zones (TZ) and can be attributed to changes in geometry, the configuration of track components, and constitutive properties of the materials. Hence, it has been observed over the operational period that railway transition zones degrade about 4-8 times faster than the open track [7]. Moreover, the literature suggests that the amplified dynamic response in transition zones can be associated mainly to stiffness variation and differential settlement [1, 3, 4]. However, there is no complete understanding regarding the relative importance of these factors and their roles in dynamic amplification of stresses in transition zones. In addition, the current literature does not provide clear answers to the following questions: How do the different kinds of inhomogeneity affect the dynamic response of track components in railway transition zones? How does the combination of inhomogeneities (such as material non-uniformity and hanging sleepers) in transition zones affect the stress state of each track component?

In this paper, the above questions are investigated by analyzing different types of inhomogeneity associated with railway transition zones in isolation and in combination resulting in 6 different cases. The effects are evaluated for each case in terms of amplification of stress (sleeper, ballast, embankment, subgrade) and vertical displacements (rail) in the approach region of TZ with respect to the open track. Three main types of inhomogeneity mentioned in literature are studied. Firstly, the inhomogeneity due to non-uniformity of material at each level of track is considered, i.e., variation of material from ballast, sand and clay to concrete. Secondly, we consider the inhomogeneity due to displacement and traction discontinuity at the vertical interface of ballast/embankment/subgrade and a concrete structure. And lastly, we consider voids between sleeper and ballast also known as hanging sleepers [8-11] as a consequence of differential settlement. A finite element analysis was performed to analyze the cases described in the next section.

2 Methods

A linear elastic dynamic analysis was performed using a finite element model to investigate the effects of different types of inhomogeneities in a railway transition zone on the main track components, namely rail (UIC54), sleepers (concrete), ballast, embankment (dense sand) and subgrade (clay soil). The cross-section details of the track can be found in Figure 1 and the mechanical properties [12,13] of track components can be found in Table 1. In order to incorporate the dynamic effects, a moving vertical load with velocity of 144 km/hr and axle load of 80 kN was simulated. Figure 2 shows the three-dimensional finite element models of an embankment-bridge transition and of an open track (used for cases with hanging sleepers). The output from the simulations that has been compared is the maximum vertical rail displacement and the maximum Von

Mises equivalent stress in sleepers, ballast, embankment, and subgrade, in the two zones marked in Figure 3 (open track and transition zone).

Material	Elasticity Modulus	Density	Poisson's Ratio	Rayleigh damping	
	E [N/m^2]	ρ [kg/m^3]	ν	α	β
Steel (rail)	21 x10^{10}	7850	0.3	-	-
Concrete (sleeper, bridge)	3.5 x10^{10}	2400	0.15	-	-
Ballast	1.5 x10^{8}	1560	0.2	0.0439	0.0091
Sand (embankment)	8 x10^{7}	1810	0.3	8.52	0.0004
Peat (subgrade)	2.55 x10^{7}	1730	0.3	8.52	0.0029

Table 1: Mechanical properties of the materials used in the finite element model.

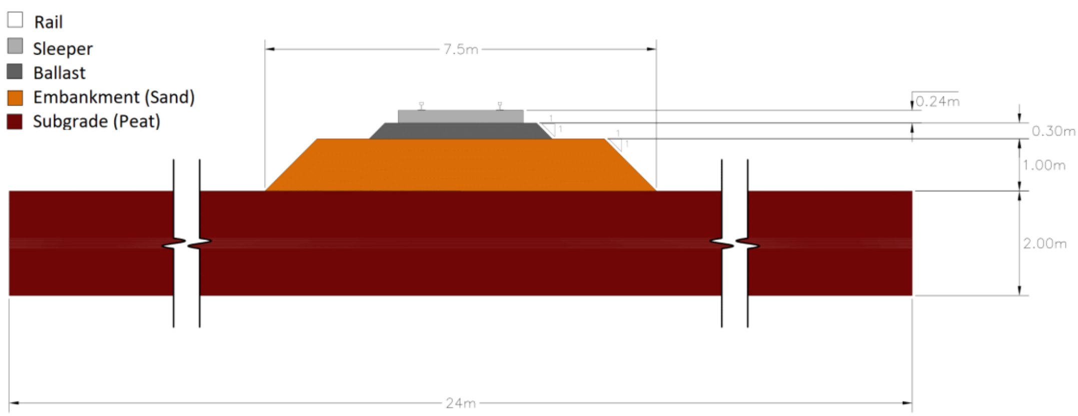


Figure 1 Cross-section details of the railway track used in finite element model.

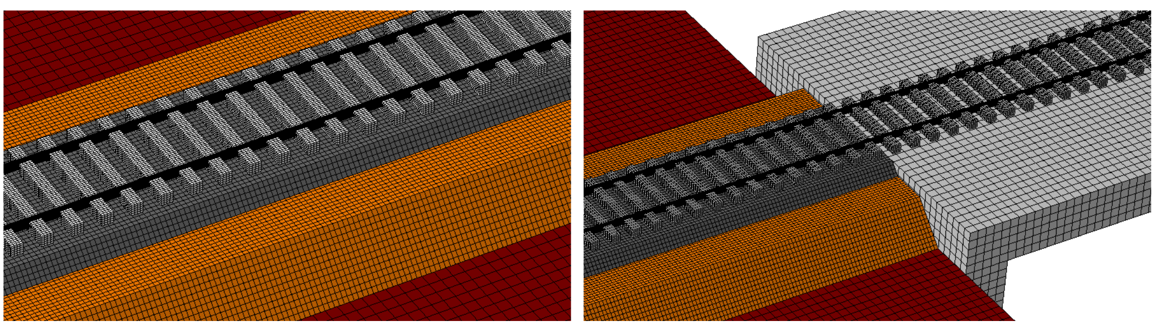


Figure 2: Finite element model of open track (left) and transition zone (right).

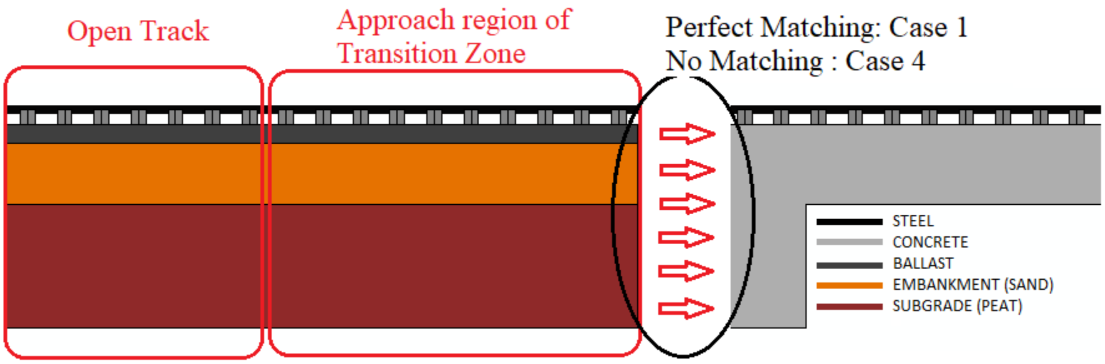
The three main sources of inhomogeneity experienced by the moving train at railway transition zones that have been considered are:

1. Material inhomogeneity due to variation in mechanical properties of materials along the longitudinal direction of the track (MI).

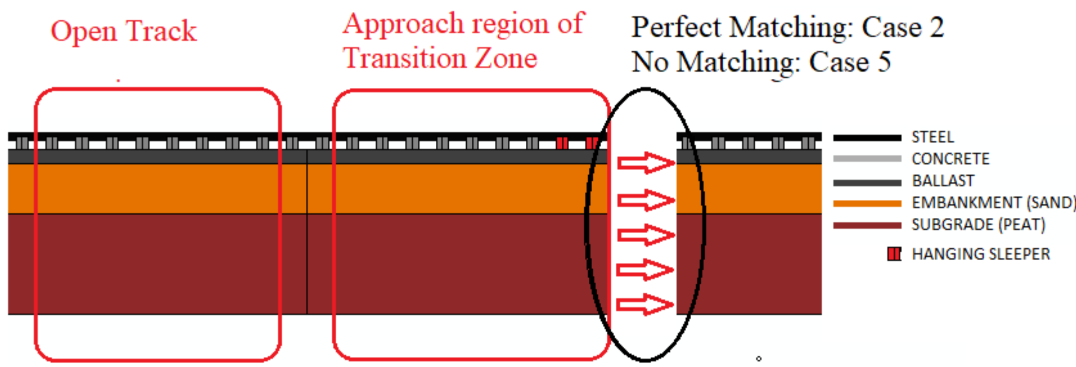
2. Displacements and traction discontinuity at the vertical interface of the transition zone. (Perfect matching of displacements and tractions at interface: PM/ tangential and normal displacement and traction discontinuity at interface or no matching: NM)
3. Hanging sleepers as a consequence of differential settlement. (HS)

The resulting cases (Figure 3) are (Note: Only cases 4 and 6 are representative of real conditions at railway TZ and the remaining cases are hypothetical):

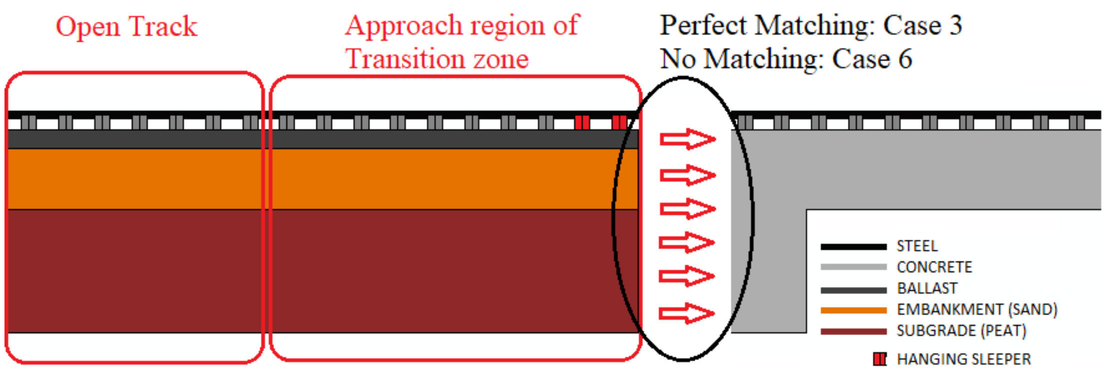
- Case 1 (Figure 3a): Material inhomogeneity with perfect matching of displacements and tractions at the vertical interface of ballast/ embankment/ soil and the concrete structure. The track acts as a continuous material with change in mechanical properties at the transition zone. (MI+PM)
- Case 2 (Figure 3b): Two consecutive hanging sleepers in open track. (HS+PM)
- Case 3 (Figure 3c): Material inhomogeneity with hanging sleepers and perfect matching of displacements and tractions at the vertical interface. (MI+HS+PM)
- Case 4 (Figure 3a): Material inhomogeneity with no matching (i.e., full sliding) of displacements and tractions at vertical interface. (MI+NM)
- Case 5 (Figure 3b): Hanging sleepers with no matching of displacements and tractions at vertical interface. (HS+NM)
- Case 6 (Figure 3c): Material inhomogeneity with hanging sleepers and no matching of displacements and tractions at vertical interface. (MI+HS+NM)



(a)



(b)



(c)

Figure 3: Details of the cases (a) Case 1 and Case 4, (b) Case 2 and Case 5, (c) Case 3 and Case 6.

3 Results

Figure 4a shows the variation of maximum vertical displacement under the load for rail in approach region of TZ ($U_{max,TZ}$) with respect to open track ($U_{max,OT}$). Figure 4 shows the percentage increase of maximum Von Mises equivalent stress ($\Delta SVM/ SVM_{max,OT}$) for each track component in approach region of TZ ($SVM_{max,TZ}$) with respect to open track ($SVM_{max,OT}$) for each of the cases depicted in Figure 3. Here, $\Delta SVM= SVM_{max,TZ}$ - $SVM_{max,OT}$. Figure 4f compares the percentage increase of the maximum Von Mises equivalent stress ($\Delta SVM/ SVM_{max,OT}$) for cases 4 and 6.

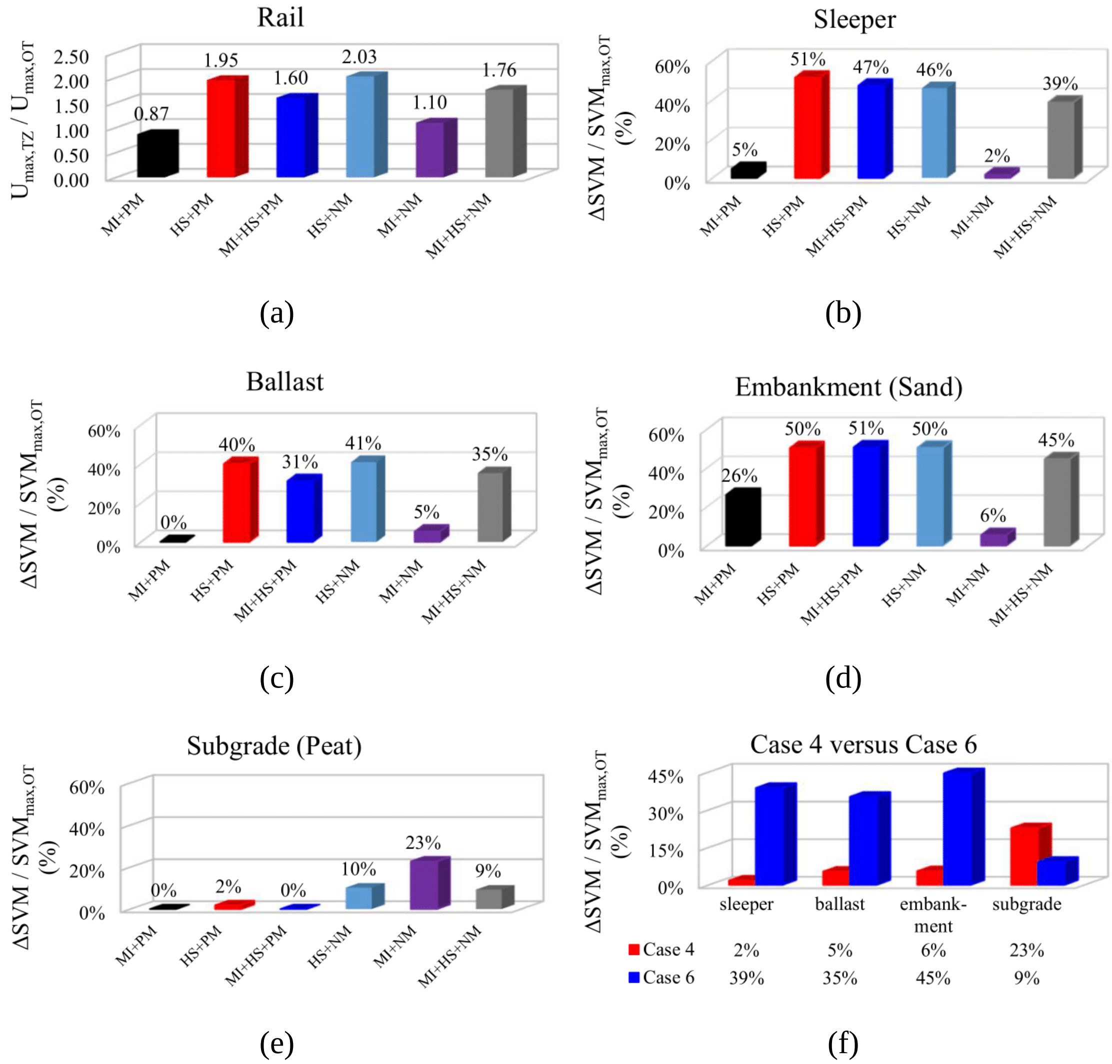


Figure 4: Percentage increase in maximum displacement and stress for the cases mentioned in Figure 3 for (a) Rail, (b) Sleeper, (c) Ballast, (d) Embankment, (e) Subgrade, (f) Case 4 versus Case 6.

The results highlight the following for each case studied in this paper:

- Case 1 (MI+PM): The embankment is the most stressed track component in this case. The ballast and the subgrade show no stress amplification in the approach region of TZ. Moreover, the rail experiences reduction in vertical displacements in the approach region of TZ when compared to open track.
- Case 2 (HS+PM): This represents hanging sleepers in open track conditions. Rail, sleepers, ballast and embankment are the most stressed track components with almost no significant effects on subgrade level. This shows that hanging sleepers

affect the upper track components (up to max. depth of 1.3 m) to a greater extent but the effect does not extend to larger depths when compared to cases with material inhomogeneity.

- Case 3 (MI+HS+PM): This is a combination of case 1 and case 2. In this case, for each track component, the stress amplifications are lower than a linear combination of the stress amplifications for individual cases. Moreover, the response lies somewhere in between the response observed in case 4 and case 5.
- Case 4 (MI+NM): In this case subgrade (peat) is the most stressed component and other track components are marginally affected in terms of stress and displacement amplifications.
- Case 5 (HS+NM): The results are like case 2 for upper track components (rail, sleeper, ballast, embankment). But for the subgrade, this case shows more stress amplification when compared to case 2 (effects can be seen at depths greater than 1.3 m)
- Case 6(MI+HS+NM): This case is a combination of case 4 and case 5. The combination behavior shows a similar pattern as case 3 but more pronounced effects for rail, ballast and subgrade and lower amplifications for sleeper and embankment when compared to case 3.

4 Conclusions and contributions

A variety of conclusions can be drawn to answer the questions mentioned in the introduction based on the results obtained. The results clearly show that the dynamic stress state of each track component is affected differently due to the presence of each inhomogeneity considered. The material inhomogeneity is more critical in terms of stress amplification for lower track components (embankment and subgrade) and the intensity was governed by the continuity of displacements and tractions at the interface of soil and structure. Although the case of material inhomogeneity with perfect displacement and traction continuity are not realistic, it helps to understand the role of these discontinuities in railway transition zones. The real behavior of transition interface lies somewhere in between the two extreme scenarios: perfect matching and no matching of displacements and tractions at transition zone. It is to be noted that the track components are least stressed in case 1 which corresponds to perfect matching. Hence, for a better performance of transition zones the interface conditions must be designed to imitate closely the conditions of perfect displacement and traction matching. Moreover, the presence of hanging sleepers was more critical for upper track components namely, rail, sleeper and ballast with very little effect of displacement and traction discontinuities.

In reference to the second question posed in introduction, concerning the combined effects of the inhomogeneities, one clear conclusion can be drawn that the stress amplification due to combination is lower than the linear combination for the individual inhomogeneities considered. There is a significant stress amplification in upper track components in all the cases with hanging sleepers, meanwhile the stress state of the embankment and subgrade is more sensitive to the material inhomogeneities and displacement and traction discontinuities. Moreover, it can be clearly seen (in case 6) that after the occurrence of hanging sleepers, the stress state of all the track components is dominated by the mechanism associated with hanging sleepers. Also, comparison of two most realistic cases (Figure 4f), which represent a perfectly straight track (case4: material inhomogeneity and displacement and traction discontinuities) and track after few months of operation (case 6: occurrence of hanging sleepers) respectively, shows that the subgrade is the most stressed component in case 4 which aids the conditions leading to case 6. Hence, it is reasonable to conclude that if the transition zone is mitigated for case 4, it would delay the processes leading to case 6.

Acknowledgements

This research is supported by the Dutch Technology Foundation TTW [Project 15968], part of the Netherlands Organisation for Scientific Research (NWO), and which is partly funded by the Ministry of Economic Affairs.

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