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3D Modeling of Transition Zone between Ballasted and Ballastless High-Speed Railway Track

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Abstract: In design and construction stages of the railway track, engineers try to avoid situations wherein track stiffness changes abruptly. Nevertheless, changing the track stiffness is inevitable, especially in the transition zone where the conventional ballasted track connects to modern ballastless track systems. In this area, track stiffness changes abruptly and it causes differential settlement, which is the main cause for degradation of tracks and foundations. Numbers of remedies have been constructed to reduce the sudden change of stiffness in transition area. The emphasis of this study is held on the assessment of the behavior of two types of the transition zones under the train moving loads. For that reason, the dynamic effect of the transition, including the displacement, acceleration and stress distribution of each part of transitions, should be analyzed. Therefore, a 3D finite element model is developed to investigate the behavior of the transition zone in response to passage of high-speed trains. The results of the dynamic analysis of a transition zone without applying any remedy have been compared with two common applicable remedies. Firstly, by installing the auxiliary rails along the ballasted and ballastless tracks, and secondly gradually increasing the length of the sleepers in ballasted area.

Key words: High-speed railway track, transition zone, auxiliary rail, sleeper length increment, moving loads.

1. Introduction

Ballasted railway tracks are one of the most common structures travelled by HST (high-speed trains). The high circulation speeds of these trains lead to increased vibrations in the tracks and nearby structures, which can affect the serviceability and maintenance costs of the tracks. Ballasted track includes continuously welded rail laid on concrete sleepers with an intervening rail pad that are supported by ballast and soil. These tracks require periodical tamping due to uneven settlements of the ballast during operation. The need for regular maintenance can significantly increase for high-speed tracks.

Ballastless (slab) track constructions offer an alternative solution due to the enormous reduction of maintenance work and the long service life with constant serviceability conditions [1, 2]. These tracks were initially used in bridges and tunnels, and, by increasing the need of HST, this technique has become the first choice for replacing the ballasted tracks. The slab track comprises rails, concrete slab, mortar layer, support concrete and soil. Seeing that, connection between ballastless and ballasted railway tracks is necessary for expansion of old railway networks. Immediate change in the vertical support and discontinuity of stiffness raises irregularity of track. These changes make the connection area as one of the major sources of problems for the track geometry that leads to more maintenance operations and disturbances in train operations. Therefore, a special design or remedy has to be set up in transition area to reduce the discontinuity of track stiffness. This area is called transition zone, and its purpose is to bring a gradual adjustment between the subgrade modulus of the slab track and the ballasted track. Many attempts have been made to improve the transition zone problem by trying to reduce the abrupt stiffness change, for instance, increasing the track stiffness on the approach by using gradually longer sleepers, installing auxiliary rail along both tracks, or

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reducing the track stiffness on the slab track by installing rail seat pads. However, none of these methods have produced much success to mitigate degradation of the track. For this reason, it is essential to understand efficiency of each approach and choose the most suitable construction method or remedy for a track under the passage of high-speed trains. The uneven settlement is another problem that causes hanging sleepers or unsupported sleepers in the vicinity of the track with higher stiffness. This phenomenon intensifies track degradation because of increasing the dynamical impact load of the passing train on the track [3-5].

The use of the FE (finite element) analysis has become widespread and popular in geotechnical practice for controlling and optimizing engineering tasks. Numerical simulation can be useful to determine long and short term behavior of the track [6]. Due to the complexity of the real engineering problems, the model simplifications for any simulation have to be considered to save time and money.

To solve the problem of the railway transition zone, the dynamic effect of the transition should be analyzed, including the displacement, acceleration and stress distribution of each part of transitions. In this study, 3D finite element models have been developed to compare the behavior of a transition zone under passage of high-speed trains. No field tests were conducted specifically for this work. To compensate for the absence of targeted field tests, the plan was to look at the possible effect of track stiffness difference using two different methods. Those methods are installing auxiliary rails along both tracks and gradually increasing the length of the sleepers in the ballasted track section [7, 8]. Consequently, the main objective of this study is the assessment of different transition zones' behavior under passage of the high-speed train moving loads.

2. Geometry and Material Properties

2.1 General Properties

The length of the ballasted track is 50 m including 83 standard concrete sleepers (B70) and center to center distance of 60 cm. The sleeper cross-section is rectangular 20 × 20 cm, and 2.5 m long, which is the modification of the standard sleeper according to Witt [9]. The cross-section of the ballasted railway track has been shown in Fig. 1.

The ballastless track dimensions are adopted from the Rheda 2000 system, which is specifically introduced for the high-speed ICE (intercity express) trains in Germany. This system is built with CBL (concrete boundary layer), HBL (hydraulic bonded layer) and FPL (frost protection layer). The slab track length is 30 m and it contains 46 double-block sleepers embedded in concrete and center to center distance of 65 cm. Ballastless track cross-section can be seen in Fig. 2.

Material properties of the ballasted track models have been obtained from Correia et al. [10], and material properties of the ballastless track in this study have been used, as stated in Heunis [11]. In Table 1, all material properties have been shown.

Both tracks have been supported by three layers subgrade. Depths of the upper layers and the last layer are 2 m and 20 m, respectively. This total depth of 22 m insures that no wave reflection happens at the boundaries in the dynamic analysis.

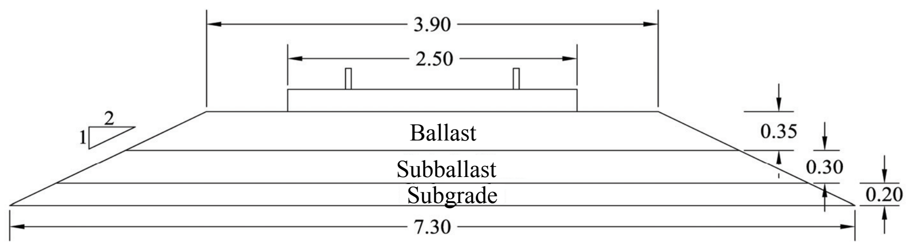

Fig. 1 Cross-section of ballasted track section (units in m).

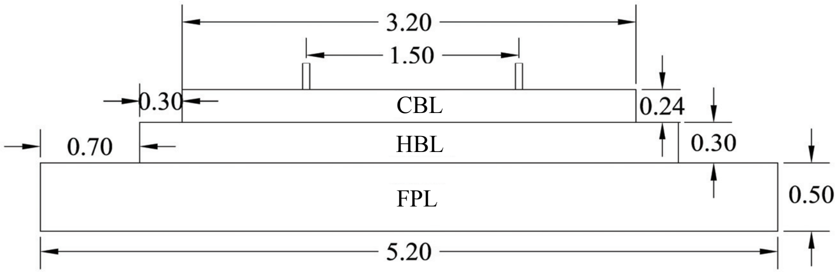

Fig. 2 Cross-section of ballastless track section (units in m).

Table 1 Material properties.

Solid elements	Density (kg/m^3)	Young's modulus (GPa)	Poisson's ratio
Rail	6,186	210	0.30
Rail pad	1,950	0.21	0.30
Ballast sleeper	2,054	30	0.20
Slab sleeper	2,400	70	0.20
Ballast	1,800	0.2	0.20
Subballast	2,200	0.3	0.20
Capping layer	2,200	0.4	0.20
CBL	2,400	34	0.20
HBL	2,400	5	0.20
FPL	2,400	0.12	0.20
Subgrade 1	2,000	0.05	0.34
Subgrade 2	1,950	0.087	0.30
Subgrade 3	1,950	0.21	0.30

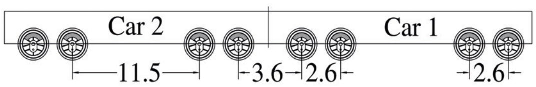

Fig. 3 Loading configuration (not scaled) (units in m).

Train load is modeled as the sequence of discrete pulses loads at the rail nodes. Therefore, the spacing of the loading nodes are divided by the train speed results to time step of calculation, and the software automatically applies it to the analysis model as a dynamic nodal [12-14]. Fig. 3 illustrates the loading configurations adopted from the UIC (International Union of Railways) code, including four bogies of two passenger cars with the axial load of 180 kN and train speed of 300 km/h.

Applying symmetry is a very effective way to increase the convenience of modeling and decreasing the analysis time. If the geometry of the structure and loading is symmetrical, half of the model can be used to decrease the number of elements and create an economic model that reduces analysis time. Here, the symmetric conditions have been taken into account, assuming that loads have the symmetric distribution over the track. Moreover, the elastic/viscous boundary elements are implemented as ground surface springs for dynamic analysis while the bottom of the model is assigned a fixed condition (displacement constraint) to simulate bedrock conditions.

2.2 Transition Zone

Ballasted and ballastless tracks show different dynamical behavior under passage of a train and wherein two tracks meet, which will have more intriguing dynamic effect to both vehicles and the tracks. To mitigate this effect, two types of the remedies that are mostly designed according to the transition zones in the vicinity of bridges have been introduced. These remedies are practical designs that have been used in many different tracks [15-17]. In fact, the basic theoretical aspects of changing the support stiffness at connection area are the same. Hence, most of the improvements can be used in the transition area of ballasted and ballastless tracks. Both sleeper length increment and auxiliary rail installation are applicable to the superstructure of a track. These remedies are based on enhancing the stiffness of the ballasted track gradually before the ballastless track [18].

Fig. 4 illustrates a 3D model of a transition zone after meshing with abrupt changes in stiffness between two tracks. In order to decrease computation time, upper layers, which are nearby the loads, have

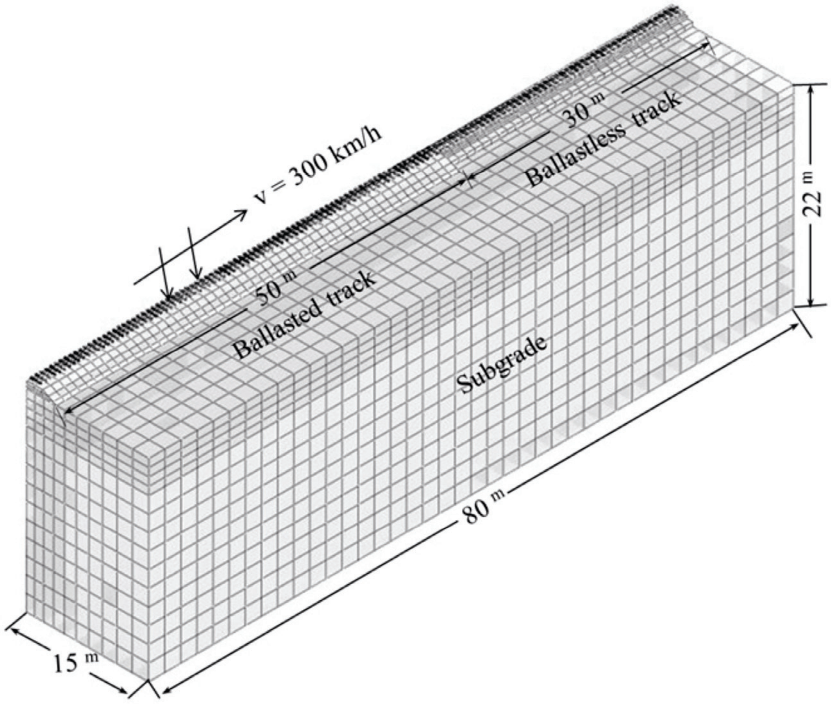

Fig.4 3D finite element model (Midas GTS NX).

finer mesh in comparison with substructure that are far from loading area.

2.3 Auxiliary Rail

One of the common methods to improve the behavior of a track in vicinity of transition zone is installing auxiliary rails. Each auxiliary rail has 30-m length that 20 m of it lays on the ballasted side and 10 m on the slab track. These rails have the same properties as main rail, and their distance from the adjacent main rail is 450 mm. Here, all basic dimensions of the model have been obtained from Plotkin and Davis [19]. Nevertheless, the rail track is a complicated structural system; Therefore, some of the actual structural components have to be neglected or modified accordingly. For instance, it is assumed that the auxiliary rail is directly connected to sleepers without having an intermediate medium and pads. However, it should be noted that the use of pads would have impacts on dynamic response of track in transition zones and could improve the behavior of this method.

2.4 Increase Track Stiffness with Longer Sleepers

This approach is based on AREMA Plan No. 913-5 [16], which is applicable for the ballasted section of transition zone. Here, the sleeper length has gradually increased from 7.5 m before reaching the slab track. The increment of sleepers' length should be applied in three steps. Each step includes four sleepers with the same length. Sleepers lengths for the first, second and third steps are 3.05 m, 3.35 m and 3.65 m, respectively, and no change has been made to the distance between sleepers.

3. Results and Discussion

Figs. 5 and 6 show that, when the load is traveling from lower stiffness region to the higher stiffness region, there is a clear reduction of the deflection on top of the rail and subgrade surface. As expected, the lower deflection can be seen in the higher support stiffness section of the track.

Reductions of subgrade differential settlement in transition zone which are 14.3% for auxiliary rail and

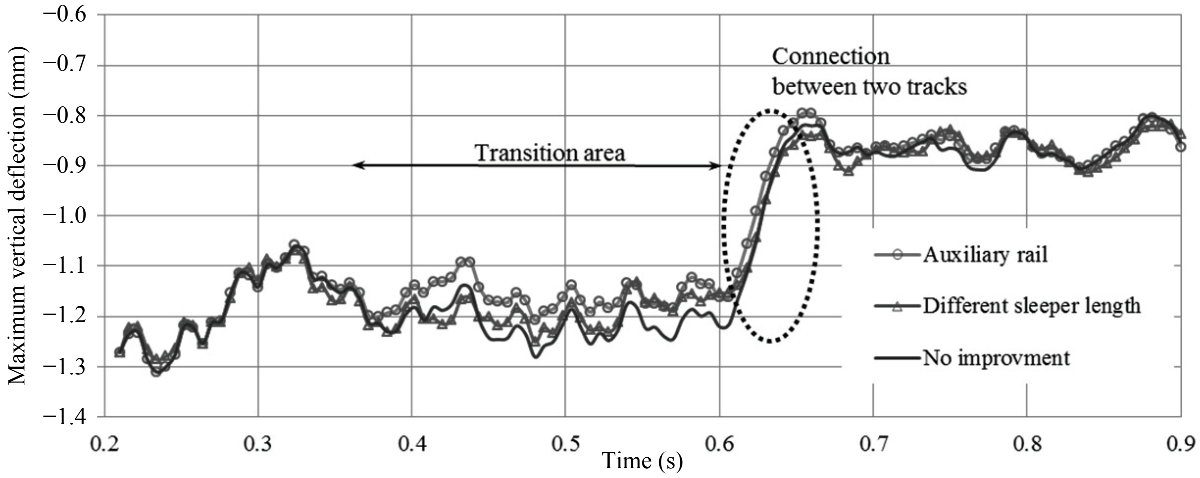

Fig. 5 Maximum vertical deflection on the rail.

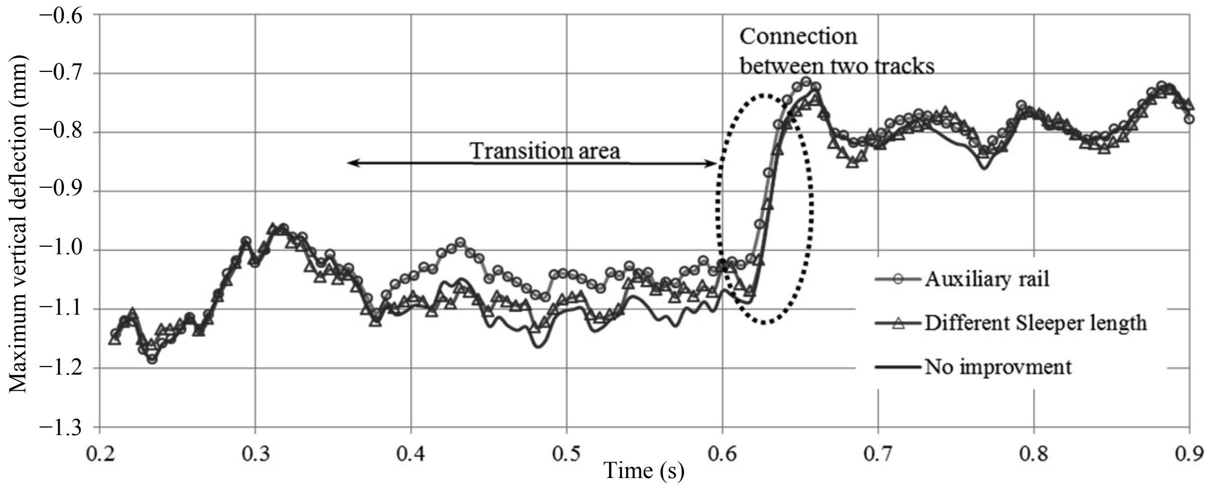

Fig. 6 Maximum vertical deflection on the subgrade.

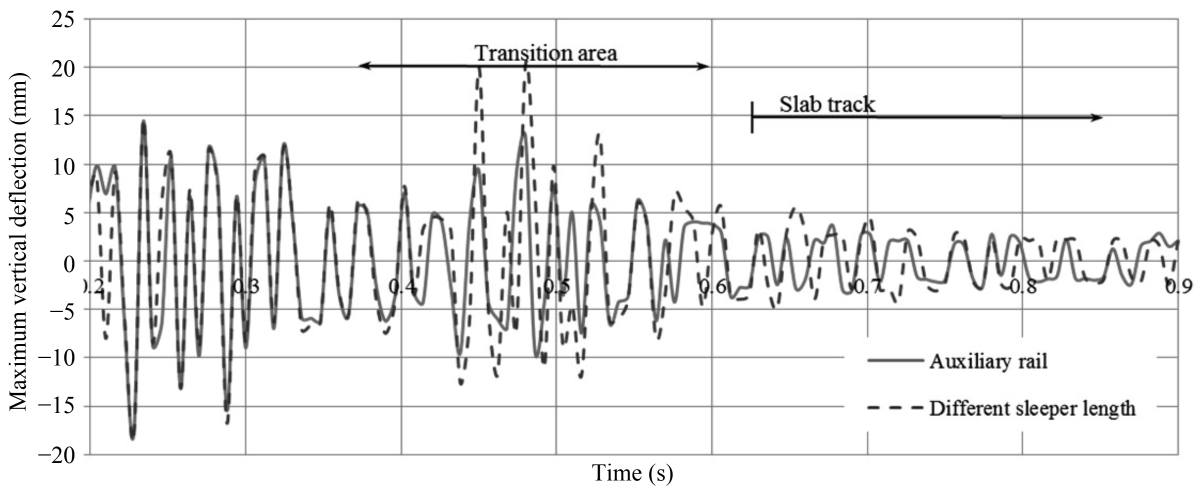

Fig. 7 Maximum vertical acceleration on the subgrade.

11.4% for sleeper length increment compare with no improved area for one passage of the train. The auxiliary rail clearly indicates smoother transformation in comparison with sleeper length increment. Moreover, the pick of the diagrams at connection between two tracks for the auxiliary rail is smaller than others that present less dynamic impact on the slab, as well as more passengers comfort.

In the point of vertical acceleration on subgrade, Fig. 7 shows high fluctuation of acceleration in vicinity of the interface of two tracks, which is due to the sudden change of stiffness in that area. There is a rapid decrease of acceleration at the interfaces of two tracks where the support stiffness increases rapidly. It can be seen that auxiliary rail provides an acceptable transformation between the two support stiffness regions, as well as strong reduction in fluctuation at the interface in compare to the increment of sleeper length.

4. Conclusions

Two widely known remedies for connection area between ballasted and ballastless tracks have been modeled to study their effects on the transition zones under passage of high-speed trains. A conclusion about the performance of these approaches has been made on the basis of vertical deflection on top of the rail and the subgrade. Maximum vertical acceleration on the subgrade of those two remedies has also been compared.

Numerical simulation of a transition zone without improvement indicates that abrupt change of the stiffness generates a very sensitive zone under the passage of the train. To minimize all undesired effects on a track in this region, it is essential to contemplate different available remedies.

The auxiliary rail installation shows a high rate of track dynamic improvement. It provides with much-needed smoother transformation to reduce the impact causing due to the sudden change in stiffness. Increment in length of sleepers has not shown a great effect, but it still can enhance the track behavior in the transition zone, and its performance can be promoted by reducing the distance between the sleepers.

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