



INVESTIGATION OF DYNAMIC BEHAVIOR OF SUPERSTRUCTURE TRACK RAILWAY IN TRANSITION ZONE

Jabbar Ali Zakeri, Vida Ghorbani

School of railway engineering, Iran University of science and technology, Iran

Abstract

Railway Track transition zone is where the track stiffness changes abruptly. It happens where the slab track connects to a conventional ballasted track, in track railway at the abutments of open-deck bridges, at the beginnings and ends of tunnels, at road and railway grade crossings and at locations where rigid culverts are placed close to the bottom of sleepers.

In this paper, ballasted track and slab track are simulated by two-dimensional model with two layer masses. Transition zone is divided into 3 segments. The length of each segment is 6 meters. Each of them has different specification and stiffness. The model of track consists of a Timoshenko beam as a rail and slab, lumped mass as sleepers and both spring and damper as ballast, subgrade and railpad.

The results of the dynamic analysis are presented and compared in two circumstances, considering the transition zone and the absence of it.

Keywords: Transition zone, Dynamic behavior, Railway track, rail pad, track vertical stiffness

1 Introduction

In design and construction of railway and underground, sometimes we face situations that track stiffness changes abruptly. They usually occur at abutments of open-deck bridges, at road and railway grade crossings, at the beginnings and ends of tunnels, where the slab track connects to a conventional ballasted track. In these regions, design and construction of special superstructure is necessary. The purpose of transition zone is to gradual adjustment between subgrade modulus of slab track and ballasted track. Track reaction to wheel force is related to track stiffness and other factors. During train movement onto two tracks with different stiffness, there will be an abrupt change in response of track in connection area [1]. One of the track problems is severe change of its vertical stiffness. In transition zone, due to variations of track vertical stiffness, vertical level of running wheel changes. This change in elevation causes vertical acceleration imposition on running coach. Variable accelerations cause vertical dynamic load to change. The level of variations depends on vertical displacement of rail in both sides of transition zone, train speed, track modulus variations and other factors. Sudden change in track vertical stiffness leads to uneven deflection which makes abrupt change in vertical level of vehicle's wheels. This change in elevation will excite the train component, i.e. the wheels, bogies and coach which in turn leads to vertical train-track interaction forces that are dynamically amplified in the transition zone [2].

A great deal of researches has been performed about this subject which design and construction of transition zone [3] and investigation of dynamic forces near bridge abutments [4], [5] can be pointed out.

2 Modeling of Railway track

The objective of this paper is to investigate in dynamic behavior of transition zone. Consequently for comparing behavior of transition zone with ballasted track and slab track, a track with 54 meters length is simulated that the first 18 meters is ballasted track, middle 18 meters is transition zone (transition zone is modeled by slab track with variation of vertical stiffness along rail) and the last 18 meters is slab track.

In modeling, two kinds of track structures are investigated as follows:

- 1- Traditional ballasted track consist of rail, sleepers, railpad and elastic ballasted subgrade
- 2- Slab track consist of rail, railpad, concrete slab that is placed on elastic subgrade.

For dynamic analysis, longitudinal section of ballasted track is simulated as two layer masses (rail as a beam and sleeper as lumped mass) on discrete supports and slab track is modeled as two beams on discrete supports by using MATLAB software. In other words, the only difference between modeling of ballasted track and slab track is that in the ballasted track lower layer (sleeper) is modeled as a lumped mass, while the lower layer of slab track (concrete slab) is simulated as a beam with bending stiffness. In this analysis half of the track is simulated in two-dimensions because of track's symmetry in section [6]. In analysis of ballasted track and slab track, supports of rail are considered as nodes and the length of elements is 0.6 meter. In order to gradual change of vertical stiffness in transition zone, transition zone is divided into three 6-meter segments. Stiffness and damping of railpad and subgrade increase step by step from the value in ballasted track to the value in slab track. Moreover slab's moment of inertia increases step by step. For this purpose, the thickness of slab has to increase step by step.

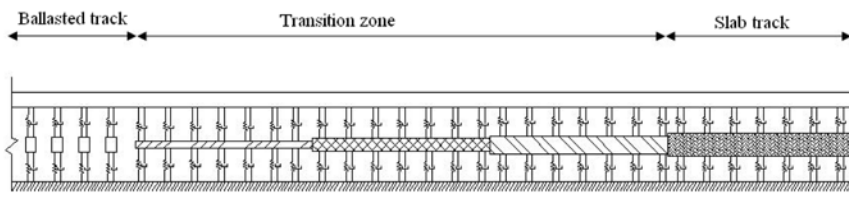


Figure 1 Track modelling with two layers masses

3 Formation of track motion's equations matrix and solving it

The equation sets of the complete system motion are obtained by assembling the equations of motion regarding to each component of the track. At the end total equation is as follows:

$$[m]\{\ddot{Z}\} + [C]\{\dot{Z}\} + [K]\{Z\} = \{P(t)\} \quad (1)$$

Where $[m]$, $[C]$ and $[K]$ are mass matrix, damping matrix and stiffness matrix of system respectively, that can be obtained by putting the matrix of each component in the relevant place of total matrix.

In order to obtain mass matrix of rail, each element of rail is assumed as a beam segment which consists of nodes at the beginning and the end of element. Each node has two degree of freedom (vertical displacement and rotation about the perpendicular axis to the plane). The mass of each element of rail is obtained by consistent mass matrix. Hence mass and stiffness matrix of rail elements are as follow:

$$M_r = \frac{\bar{m}L}{420} \begin{bmatrix} 156 & 22L & 54 & -13L \\ 22L & 4L^2 & 13L & -3L^2 \\ 54 & 13L & 156 & -22L \\ -13L & -3L^2 & -22L & 4L^2 \end{bmatrix} \quad K_r = \frac{2EI}{L^3} \begin{bmatrix} 6 & 3L & -6 & 3L \\ 3L & 2L^2 & -3L & L^2 \\ -6 & -3L & 6 & -3L \\ 3L & L^2 & -3L & 2L^2 \end{bmatrix} \quad (2)$$

Where \bar{m} rail mass per unit length, L is the length of element, E is modulus of rail and I is the moment of inertia of the rail. Mass matrix and stiffness matrix of complete rail are obtained by assembling of each element's matrix. Damping matrix of rail is obtained by next equation:

$$[C_r] = \alpha[M_r] + \beta[K_r] \quad (3)$$

Sleepers are modeled as lumped masses. So mass matrix, stiffness matrix and damping matrix of sleepers are as follows:

$$[M_s] = \frac{M_s}{2} \begin{bmatrix} 1 & 0 & 0 & \dots & \dots & 0 \\ 0 & 1 & & & & \\ 0 & & 1 & & & \\ \vdots & & & \ddots & & \\ \vdots & & & & \ddots & \\ 0 & 0 & \dots & \dots & \dots & 1 \end{bmatrix} \quad [C_p] = C_p \begin{bmatrix} 1 & 0 & 0 & \dots & \dots & 0 \\ 0 & 1 & & & & \\ 0 & & 1 & & & \\ \vdots & & & \ddots & & \\ \vdots & & & & \ddots & \\ 0 & 0 & \dots & \dots & \dots & 1 \end{bmatrix} \quad [K_p] = K_p \begin{bmatrix} 1 & 0 & 0 & \dots & \dots & 0 \\ 0 & 1 & & & & \\ 0 & & 1 & & & \\ \vdots & & & \ddots & & \\ \vdots & & & & \ddots & \\ 0 & 0 & \dots & \dots & \dots & 1 \end{bmatrix} \quad (4)$$

Thus motion equation of sleepers is given by:

$$[M_s][\ddot{Z}_s] + [C_p][\dot{Z}_s(t) - \dot{Z}_r(x,t)] + [C_b][\dot{Z}_s] + [K_p][Z_s(t) - Z_r(x,t)] + [K_b][Z_s] = 0 \quad (5)$$

Where K_p, K_b are stiffness of railpad and ballast, C_p, C_b are damping of railpad and ballast and $Z_r(x,t), Z_s(t)$ are vertical displacement of rail and sleeper in time (t) respectively.

Each element of concrete slab is modeled as a simple beam which: \bar{m} is slab mass per unit length, E is modulus of slab and I is the moment of inertia of the slab.

In calculations instead of vehicle, four moving loads are considered to transit on the track. It is assumed that in the primary step, first load places on first node. In the next step, after a period of time (Δt), load moves forward. It should be taken into consideration that regarding to the velocity if the load places on the node one array of stiffness matrix gets value from the force vector and if it places on the beam element, four arrays of stiffness matrix get value. In order to solve the differential equation and attaining the results, Newmark numerical method has been applied.

Table 1 Dynamic specifications of track components

Component track		Mass [kg/m]	Stiffness [kN/m]	Damping [kN.S/m]
ballasted track	Rail (UIC60)	60	-	-
	Railpad	-	200×10 ³	28
	Sleeper	320	-	-
	Ballast	-	46×10 ³	180
slab track	Railpad	-	375×10 ³	135
	Slab	1876	-	-
	subgrade	-	60×10 ³	180

table 1 shows dynamic specifications of track components. According to table 1. In the first 6 meters of transition zone, the value of stiffness and damping of railpad are 243.75×10^3 kN/m and 54.75 kNs/m and in the middle 6 meters of transition zone are 287.5×10^3 kN/m and 81.5 kNs/m and in the last 6 meters of transition zone are 331.25×10^3 kN/m and 108.25 kNs/m respectively.

4 Comparison of track dynamic behavior: assuming transition zone existence and absence

Results of maximum displacement, acceleration and vibrational velocity have been discussed in two cases of assuming transition zone and its absence.

For obtaining the maximum displacement graph, the value of maximum displacement in the time history of the relevant node, should be calculated. Fig. 2 shows in the absence of transition zone, displacement difference in a length less than 2m reaches to its own maximum and displacement varies from 1.17mm to 0.7mm. Therefore, acceleration varies suddenly in a short length, and causes the track to oscillate that can be followed by destructive effects. However according to Fig. 3, displacement difference providing that transition zone exists, occurs step by step in 3 stages along 18 meters.

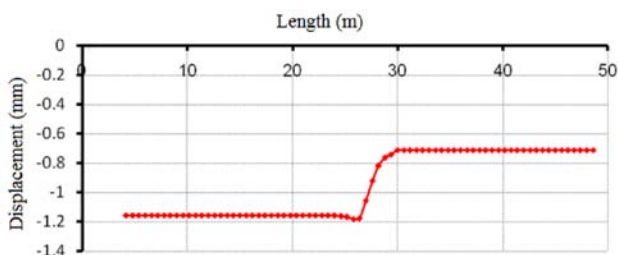


Figure 2 Maximum displacement of rail in the absence of transition zone

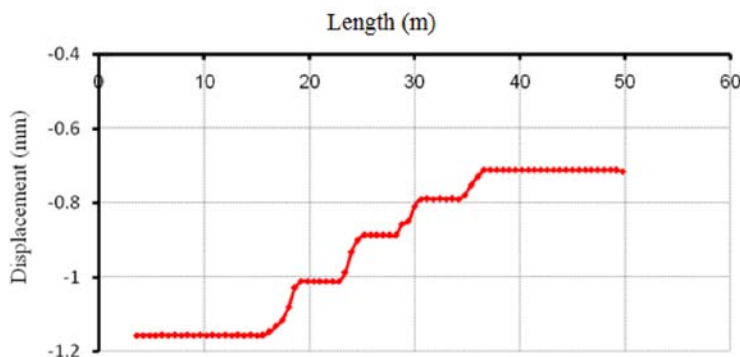


Figure 3 Maximum displacement of rail assuming transition zone existence

According to Fig. 4, in the connection point of ballasted track and slab track, maximum vertical, increases abruptly from 6.6m/s^2 to 8m/s^2 , so there is a variation in rail acceleration about 1.4m/s^2 . In the slab track part, vibrational acceleration reaches from 3.1m/s^2 to 3.6m/s^2 . In the other words, in the ballasted part there is 21% increase in the acceleration, while in the slab track, the mentioned value is 16%.

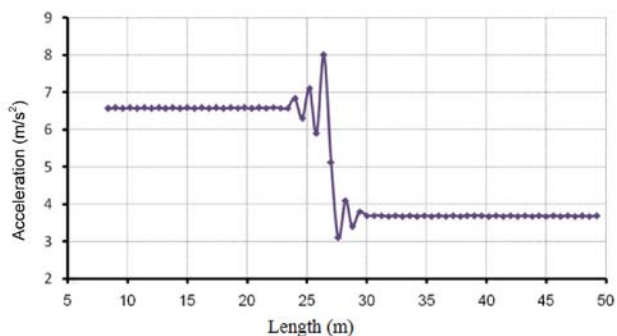


Figure 4 Maximum acceleration of rail in the absence of transition zone

Fig. 5 indicates that oscillation's difference has the greatest amount from the ballasted track to the first part of transition zone.

To state the matter differently, vibrational acceleration has reached from 6.6m/s^2 to 7.1m/s^2 which shows a 7.5% increase. This raise has decreased noticeably (21% to 7.5%) which indicates the importance of transition zone. Also, the acceleration values in the 4 stages, has not decreased similarly. Thus the relation between acceleration and stiffness changes is not linear.

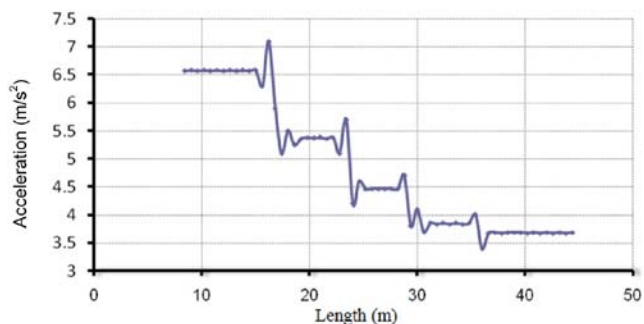


Figure 5 Maximum acceleration of rail assuming transition zone existence

According to Fig. 6, railpad force in ballasted track, is around 42 kN that this force increases to 70 kN in slab track. Railpad force depends on two factors. The first factor is elevation difference between rail and sleeper in ballasted track and elevation difference between rail and slab in the slab track. The second factor depends on the stiffness of railpad.

The stiffness of railpad in ballasted track is 200 MN/m and in the slab track equals to 375 MN/m. So, trends of the railpad force changes in track cannot be discussed. But the issue that matters is the abrupt increase in the force of railpad in the ballasted track and slab track connection. According to Fig. 6, in a short period of time and along a short length, force increases from 40 kN to 80 kN which this increase can have harmful effects.

In Fig. 7, the railpad force in the ballasted track reaches from 42 kN to 58 kN and shows an increase of 38%. This means that transition zone causes the force increase to drop 52%.

Fig. 8 shows the force in the ballast and subgrade. According to Fig. 8, the ballast force is approximately 43 kN and the force of subgrade is 31 kN. Furthermore, it can be seen that force increases from 43 kN to 58 kN in the mid length which shows a 35% increase in the force that is less than the force change in railpad.

In Fig. 9, the ballast force increases from 43 kN to 51 kN due to track's structure change and increases 18% which means transition zone caused force increase to drop 50%.

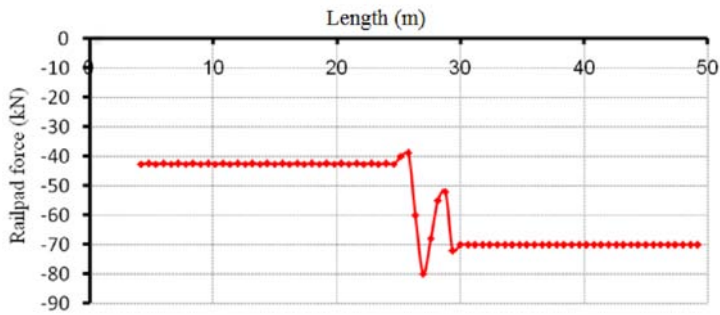


Figure 6 Maximum railpad force in the absence of transition zone

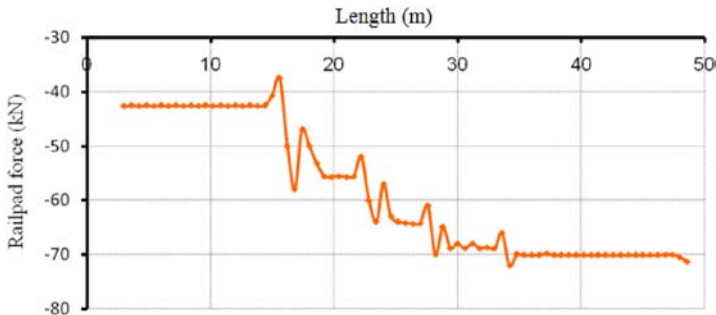


Figure 7 Maximum railpad force assuming transition zone existence

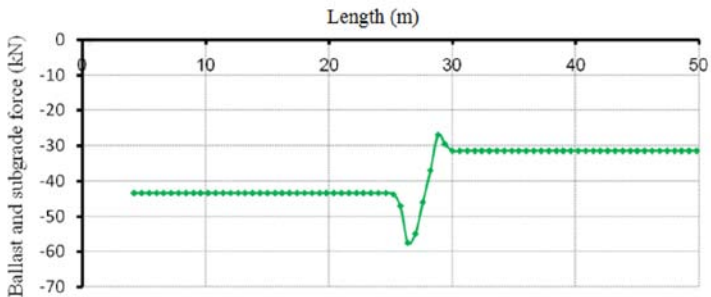


Figure 8 Maximum force of ballast and subgrade in the absence of transition zone

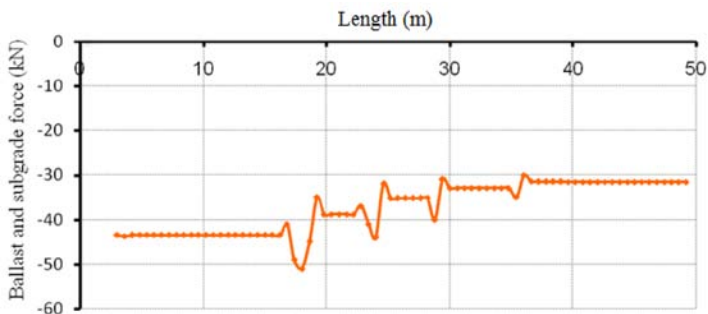


Figure 9 Maximum force of ballast and subgrade assuming transition zone existence

5 Results validation

For more comparison and investigation about the attained results, we refer to the results of reference [7]. In the mentioned research, a three dimensional finite element model is applied to study the mechanics of railway track transitions. (Fig. 10) The applied model incorporates the multi-layered nature of the sub-structure, soil and ballast nonlinearity and the interaction between the track and train. The model of track consists of rail, railpad, sleeper, ballast, sub ballast and several subgrade layers. The effect of transition length and the train speed on the track-train performance has been investigated in terms of the rail wheel interaction force and train body acceleration [10].

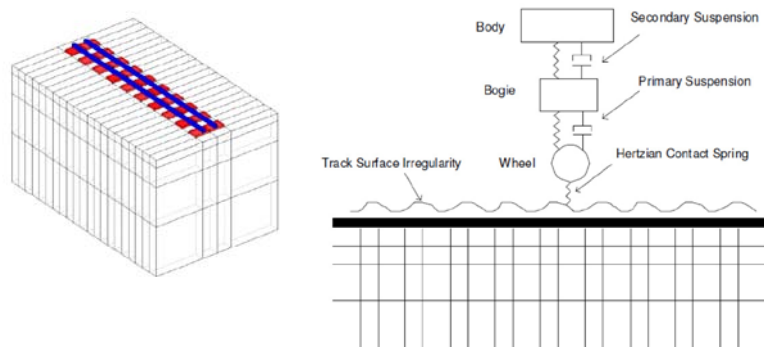


Figure 10 Schematic layout of three-dimensional coupled track-train model

Fig. 11 shows rail displacement in the transition zone under wheel loading without any voids under sleepers and while there is no geometric irregularity in the rail or track substructure. As shown in the figure, when the stiffness change varies gradually, displacement varies gradually too. This is the reason of transition zone execution.

Moreover the results of references [4], [8] and [9] can be used for comparison.

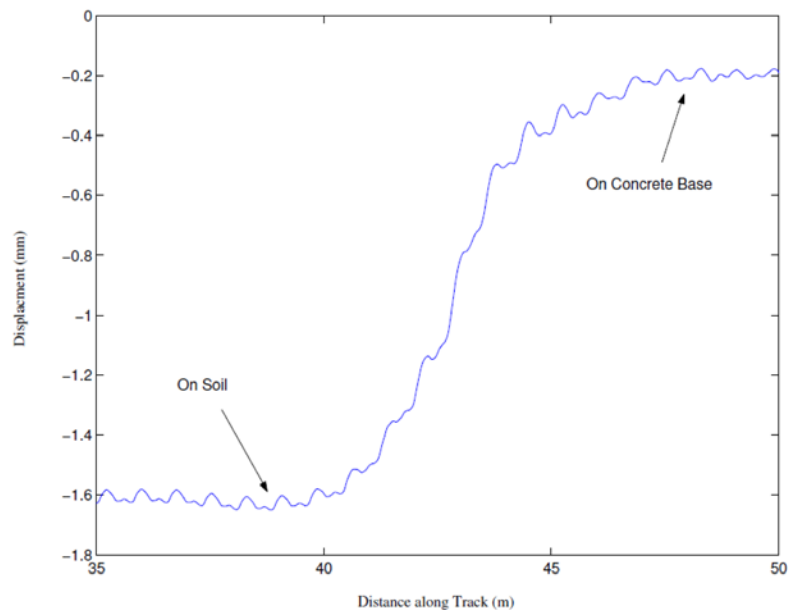


Figure 11 Rail displacement in a stiffness transition under wheel load

6 Conclusion

The results of track modeling in MATLAB software shows, vertical displacement difference and rail acceleration and velocity difference in the ballasted track and transition zone connection is greater in the slab track and transition zone connection. In the absence of transition zone, displacement difference reaches to its own peak and therefore acceleration varies suddenly in a short length, and causes the track to oscillate. But, in the case that transition zone is considered, differences will be distributed along the transition zone and moderates the shock. The vertical acceleration of rail, sleepers and slab shows that acceleration change in the rail is greater than it in the sleeper and slab. In the connection area of ballasted track to slab track, acceleration changes noticeably.

The trend of the railpad force changes from ballasted track to slab track, cannot be opined certainly but the thing that matters is sudden increase of railpad force in ballasted track and slab track connection. This condition is also applies to the ballast force when the variations are less than railpad force which can be resolved considering the transition zone.

References

- [1] Kerr, A.D.: Fundamentals of Railway Track Engineering, Simmons-Boardman Books, Inc. 2003.
- [2] Esveld, C.: Modern Railway Track, Second edition, TU-Delft, 2001.
- [3] Lotfi H.R. and Oesterle R.G.,: Slab track for 39-ton loads, structural design, R&D SN2832, Portland, Cement Association, Skokie, Illinois, USA, 99 pages, 2005.
- [4] Hunt H.E.M.: Settlement of railway track near bridge abutments, Proc. Instn. Civ. Engrs, Transp., pp. 68-73. April 1997.
- [5] Li D., Read D.: Research results digest 79, Transportation Technology Center, Inc.(TTCI), October 2006
- [6] Ishida M., Suzuki T.: Effect on track settlement of interaction excited by leading and trailing axles, QR of RTRI, Vol. 64, No. 1., Feb.2005.
- [7] Banimahd M., Woodward P.K.: 3-Dimensional finite element modeling of railway transitions, XITRACK, Proceedings 9th International Conference on railway engineering London, June 2007.
- [8] Bridge approaches and track stiffness, U.S. Department of transportation, Federal Railroad Administration, April 2007.
- [9] Fan J.J., Xia H., Zakeri J.A.: Dynamic Responses of Train –Track system to Single Rail Irregularity, Latin American Journal of Solids and Structures, Vol. 6, No. 2, pp.89-104., 2009.
- [10] Ghorbani V.: Investigation of dynamic behavior of superstructure track railway in transition zone, MSc. Thesis, Iran university of science and Technology, 2009.