



Investigation on Effect of Train Speed in Displacement of Railway Ballasted Track with Unsupported Sleepers

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ABSTRACT: One of the main problems of the damages of rail tracks which is caused by track settlement is unsupported sleeper. Due to this defect the underlying area of sleeper is not supported on the ballast and causes the sleeper displacement to increase. The increase creates vibration in the track and vehicle components and causes problems on their performance. Hence, in this study the investigation of rail displacement in tracks with unsupported sleeper has been dealt with. Three dimensional modeling of the vehicle and ballasted track has been carried out using ANSYS and SIMPACK programs. To use this software, the modeling of a flexible track in the vehicle multibody model is possible. Ballasted track which is formed from components as rail, sleeper and ballast, has been considered to be flexible. In simulating the vehicle all of its main components have been considered and damping and stiffness values of bogie suspension systems have been considered to be nonlinear. The results obtained from numerical simulation have good agreement with field test results. The results show that the speed of the vehicle on the track displacement with less than four unsupported sleepers has no effect, but by increasing the number of unsupported sleepers, the effect of increasing velocity would be considerable.

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1- Introduction

In ballasted tracks due to drooping and rugged arrangement of ballast grains, a portion of the rail would remain unsupported. This defect could be created due to improper tamping of ballast layers, traffic increase of rail tracks, improper weather conditions or other factors. By increasing the contact force of wheel/rail the possibility of vibration increase and subsequently defect in components of the track and suspension system of the vehicle would be created.

During the past years a lot of studies have been done in order for investigating the dynamical behavior of railway tracks. In most of these studies, concentrated masses have been used for modeling the track and in some of the studies the dynamical behavior of the track has been dealt with. In recent years with the development of multibody dynamic simulation program, analysis of flexible tracks in these program has been enabled using the capability of mixed simulation. By using this capability, the model of flexible track is modeled in Finite Element (FE) program, and then in order for connection between vehicle and the track it is inserted into multibody program. Also, this capability could consider small deflections of the track which causes vibration in track components and vehicle. Consequently, the results obtained from this analysis could provide more precise results for researchers in the field of dynamic studies.

In past years the effects of track defects have been studied by numerous researchers. For example, Zakeri and Ghorbani [1] studied the hardness and changes of stiffness and dynamic

behavior of the system in ballast track. Zakeri et al. [2] studied the response of the track in a track with unsupported sleeper by considering the interaction of track-train. Lorenzo et al. [3] studied all kinds of rail tracks using flexible track model. Thompson et al. [4] studied the existence of unsupported sleepers in ballast tracks. Mosayebi et al. [5] studied ballasted tracks having unsupported sleepers for their mechanical performance by considering various models of bogie. Lee et al. [6] performed the diagnosis of unsupported sleepers using FE analysis and field test. Kaewunruen and Remennikov [7] studied the analysis of free vibration of unsupported sleepers. Bezin et al. [8] studied the deficiency superelevation effect of the rail on the tracks with unsupported sleeper by using flexible track model. Aceituno et al. [9] studied the behavior of flexible rail using FE method and reduced modal method. Lei and Wang [10] performed the dynamical analysis of train and slab track by using FE method. Ji et al. [11] studied the effects of wind force and irregularities of the track by considering flexible track and flexible body.

Considering the aforementioned literature survey, it can be deduced that effect of vehicle speed on track displacement across unsupported area has not been investigated in the field of vehicle-track interactions. Moreover, in Multibody dynamic programs in which 3 Dimensional (3D) modeling of the vehicle is performed, the track is considered as rigid. However, in this study a flexible simulation is considered for the track utilizing integration of ANSYS and SIMPACK programs. Hence, the simulation is capable of computing track displacement occurring due to vehicle passing on a flexible track. The obtained simulation results in this study were verified with the results of field test which were carried out in the track of Tehran railway track.

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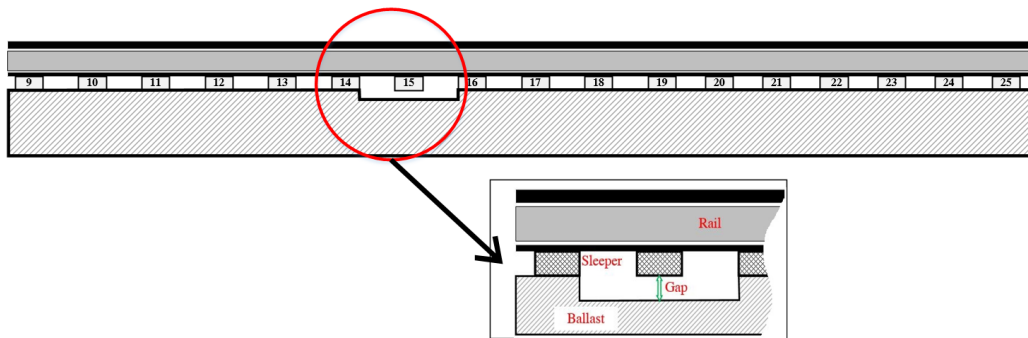


Fig. 1. View of unsupported sleeper

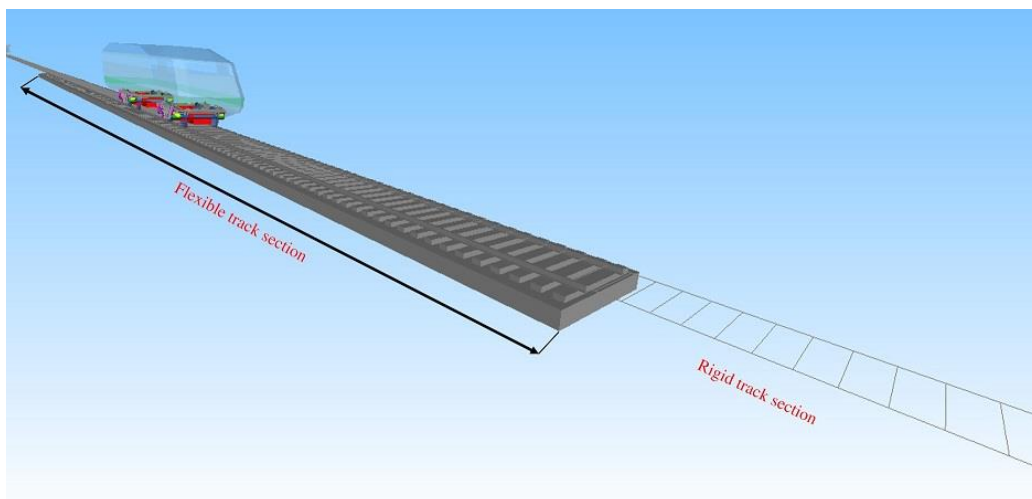


Fig. 2. The flexible track in SIMPACK program.

2- Unsupported Sleeper

In ballasted tracks when due to defects of the track there is not enough ballast under the sleeper, it causes distance between sleeper and ballast to be created. In this condition the sleeper would be hanging from the rail and so the support of the sleeper would be partially or completely lost (Fig. 1). The existence of such problem causes force changes in the area of track and contact force of track-train, and these changes causes vibration in vehicle. Also, the existence of such phenomena might cause the derailment of the train and disturb the performance the components of track such as sleeper and fastenings.

3- Vibration Analysis of the Vehicle-Track System

3- 1- Substructure analysis of the flexible track model

The SIMPACK program by using Co-simulation in FE program accepts mass, damping and modal matrixes as input. Here, at first analysis of substructure should be carried out and flexible track model be formed as superelement matrix before being imported into SIMPACK program. Substructure method can convert a part of the element as a matrix that points out to superelement matrix. In FE program that here ANSYS program has been used, it is required that necessary files be produced

in order to be imported into SIMPACK. Information related to mass and stiffness of flexible track is stored in superelement matrix and are created with .sub extension. Also, the geometry of model is stored with “.cdb” extension and modal analysis with “.rst” extension. In the process of analyzing the substructure, model’s degree of freedom needs to be reduced. For this purpose, it is required that Guyan method [12] be used for identifying and adjusting the number of degree of freedom points. After analyzing substructure and modal analysis, information related to mass, stiffness, geometry and modal matrixes are stored in these files, and then are prepared to be imported into SIMPACK program.

The SIMPACK program after importing the files related to mass and stiffness matrixes, modes and the geometry of flexible track model, could receive all the necessary information by creating an “.fbi” file. Fig. 2 shows a view of flexible track in SIMPACK program. In this figure the flexible track has the length of 90 m and unsupported sleeper is modeled in its middle section. The vehicle at first moves on a rigid track and then enters flexible section. Fig. 3 shows a view from unsupported sleeper. This area is located in the middle section of the flexible track.

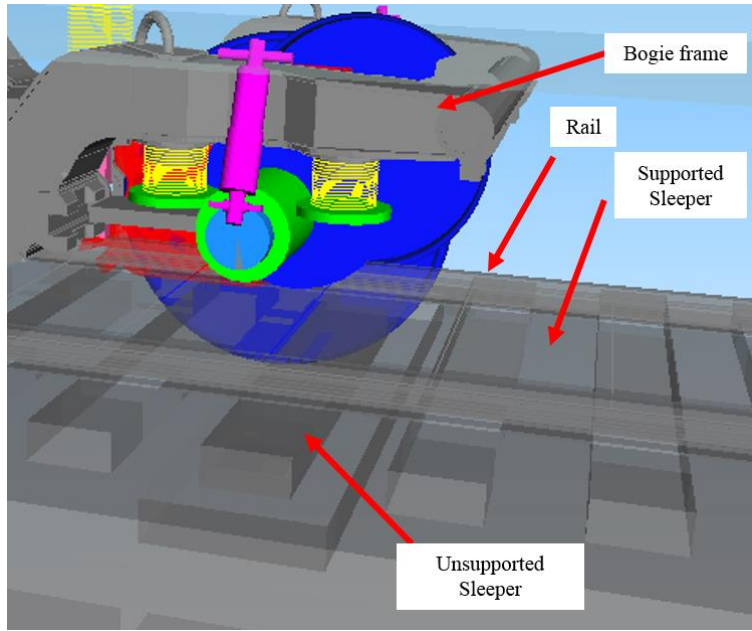


Fig. 3. Unsupported sleeper area in the flexible track section.

3- 2- Motion equations of the flexible track

Since the track is considered as flexible here, the equations of motion of the flexible track must be coupled with those of SIMPACK program.

Motion equations of flexible body are expressed in various references [13,14]. In case point P is located on the flexible body, its position could be expressed as follows [14]:

$$r^p(c,t) = A(t)(r + c + u(c,t)) \quad (1)$$

In which A is the rotational matrix used for coordination matrix from body e reference system with inertia e^I , r is the position of reference system e, and c is the position of point P in non-deformation mode in reference system $u(c,t)$ is the deformation vector of flexible body. Ritz approximation is used for deformation of flexible body with linear combination of $\varphi_j(c)$ shape function and modal coordination $q_j(t)$ [14]:

$$u(c,t) = \sum_{j=1}^{n_q} \varphi_j(c) q_j(t) \quad (2)$$

By combining Ritz approximation with Hamilton principle and by using various mathematical operations, the equation of motion would be as follows [15]:

$$M(q) \begin{Bmatrix} \dot{a} \\ \dot{\omega} \\ \ddot{q} \end{Bmatrix} + k_{\omega}(\omega, q, \dot{q}) + k(q, \dot{q}) = h \quad (3)$$

In which M is mass matrix, K_{ω} is the matrix of extended force due to gyroscope and centrifugal terms, k and h are internal and external extended forces matrixes, respectively. a , ω and q are time independent vectors of absolute acceleration, angular velocity and modal coordination, respectively. For more information, refer to reference [15].

As the flexible track does not perform a big movement of solid body, so just one part of Eq. (3) (namely modal and stiffness matrixes) would need it. According to mass matrix M, stiffness matrix K, and shape function expressed in Eq. (4), mass, stiffness, modal and extended force between wheel and rail matrixes could be expressed by Eqs. (5) to (7):

$$\phi^T = \{\phi_1, \dots, \phi_j, \dots, \phi_{n_q}\} \quad (4)$$

$$M_e = \phi^T M \phi \quad (5)$$

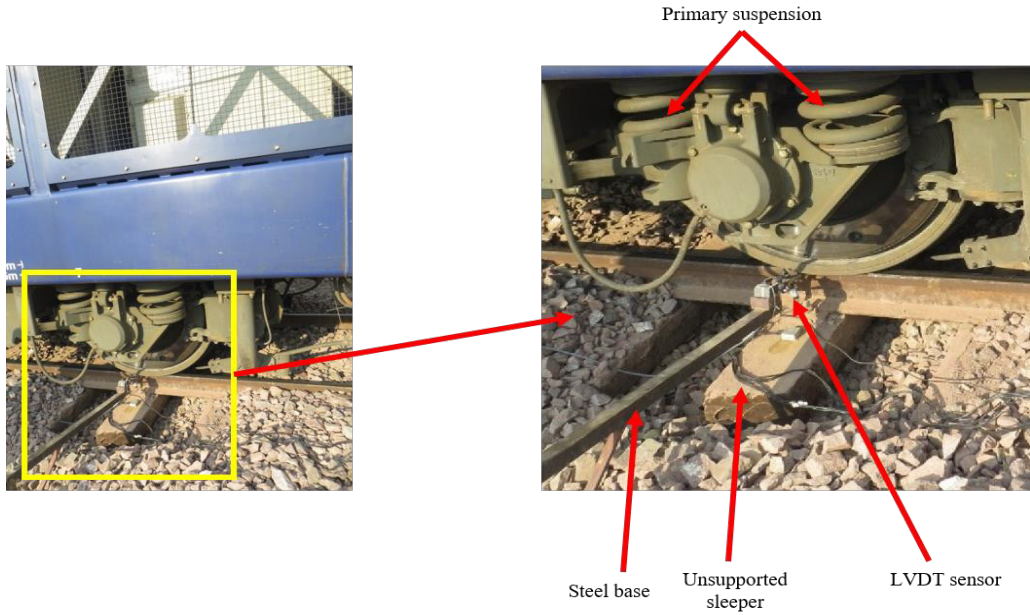


Fig. 4. LVDT sensor installed on unsupported sleeper.

Table 1. Vertical stiffness and damping coefficients of primary and secondary suspension systems [16].

Row	Parameter	Value
1	Vertical stiffness of primary suspension	1126000 N/m
2	Vertical stiffness of secondary suspension	749000 N/m
3	Vertical damping of primary suspension	100000 N.s/m
4	Vertical damping of secondary suspension	600000 N.s/m
5	Mass of wheelset	1931 kg
6	Mass of traction motor	1595 kg
7	Mass of car body	55330 kg

$$K_e = \phi^T K \phi \quad (6)$$

$$p_e = \phi^T p \quad (7)$$

In Eq. (7) the excitation of track is expressed by the force P of wheel/rail. For perpendicular function, equations of motion could be written for a set of independent equations [15].

$$M_e \ddot{q} + K_e \dot{q} = p_e \quad (8)$$

Second order linear differential equation n_q could be expressed by the following equation:

$$m_{ejj} \ddot{q}_j + d_{ejj} \dot{q}_j + k_{ejj} q_j = p_{ej} \quad (j = 1, 2, \dots, n_q) \quad (9)$$

In which m_{ejj} , d_{ejj} and k_{ejj} represent mass, damping and modal stiffness related to each mode ϕ_i , respectively p_{ej} is the extended force, d_{ejj} mentioned in Eq. (9) is resulted from Eq. (10) [15]:

$$d_{ejj} = 2D_j \sqrt{m_{ejj} k_{ejj}} \quad (10)$$

In which A is the damping ratio of the flexible track.



Fig. 5. A view of the passenger locomotive passing the test zone.

4- Field Test

In order to study the results obtained from simulation and to validate the track displacement, field test has been done. The railway track used in this study has wooden sleepers and the profile of the rail profile used in this track is from U33 type with density 7800 kg/m³.

In order for measuring the displacement of the track Linear Variable Differential Transformer (LVDT) sensor has been used. This sensor provides the measurement of displacement of track during the movement of the vehicle from test area. Fig. 4 shows a LVDT sensor installed on unsupported sleeper.

The vehicle used in this test is ER24PC locomotive. This locomotive is passenger type and is widely used in Iran for carrying passenger and freight wagons. The bogie of this locomotive is Bo-Bo and has primary and secondary suspension system. The primary suspension system is located between axle box and bogie frame and secondary suspension system is located between frame and underframe of the locomotive. In Table 1 the properties of stiffness and damping of bogie primary and secondary suspension systems have been presented. Total weight of the locomotive is 85 tons.

In order to study the track displacement measurement in the areas of unsupported sleeper and supported sleepers, the locomotive passes on the ballasted track with wooden sleepers. Fig. 5 shows a view of locomotive passing the test area.

5- Validation of the Flexible Track

For validating the flexible track model with unsupported sleepers, it is required that the numerical model be validated with field measurements. Fig. 6 shows the comparison of the results of track displacement in numerical simulation and field test on a track with an unsupported sleeper and supported sleeper.

As it could be observed, track displacement in numerical simulation has a good agreement with the result of field test. The maximum displacement of the track in the mode with one unsupported sleeper is 110% more than the maximum displacement of the track without unsupported sleeper. Also, in this figure the first increment of displacement is related to the passing of first bogie and the second increment of displacement is related to the passing of second bogie in the area with unsupported sleeper and supported sleeper.

6- Numerical Results

In this study in order to study the maximum amount of displacement of the track with unsupported sleepers, two-axle locomotive has been used. This locomotive has primary and secondary suspension systems. Simulation performed in this study was in SIMPACK program and the locomotive at first moves on the rigid track and then on the flexible track with 90 meters of length. Modeling of unsupported sleeper is in middle section of the flexible track.

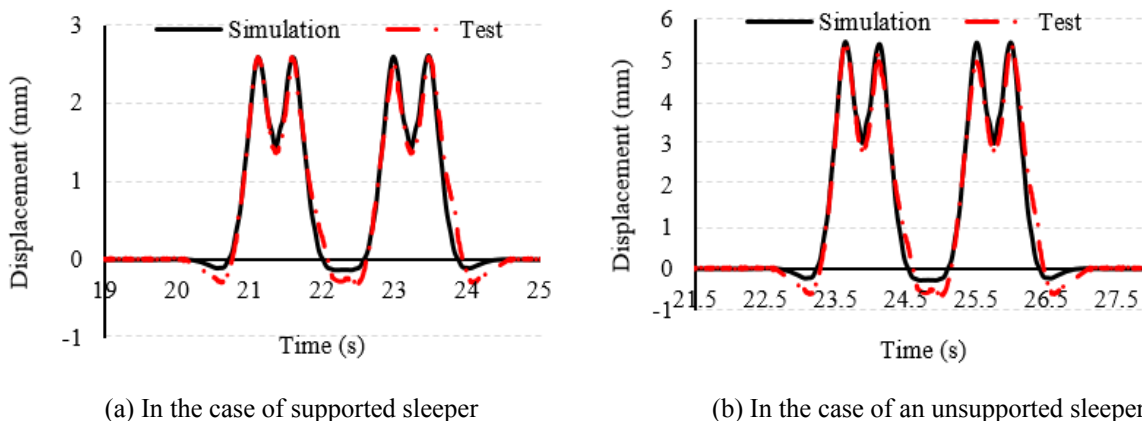


Fig. 6. Rail displacement comparison between numerical model and field test.

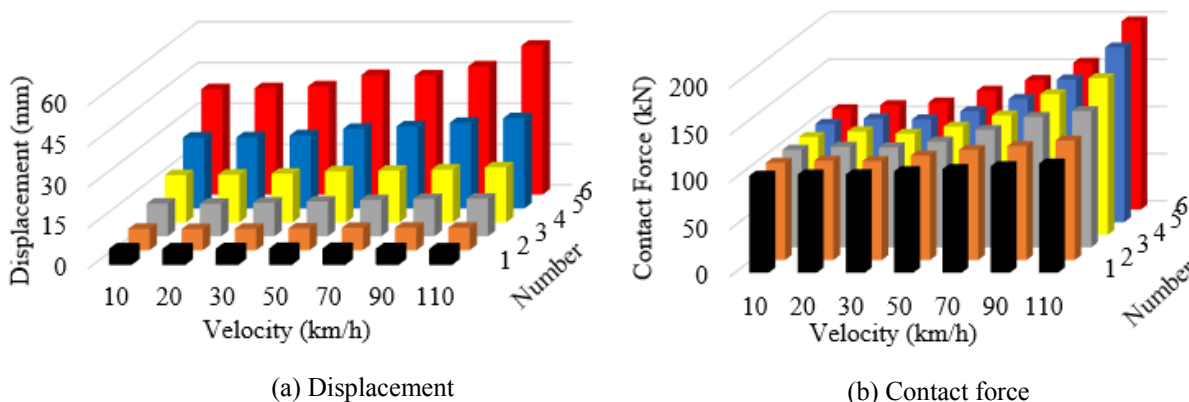


Fig. 7. Maximum of track displacement and contact force.

In Fig. 7 the changes of maximum contact force of wheel and rail displacement due to velocity changes and the number of unsupported sleepers have been shown. Figs. 7(a) and 7(b) show the maximum displacement of rail and wheel/rail contact force by considering velocity changes and the number of unsupported sleepers. As it could be observed in this figure, by increasing the velocity of the vehicle and the number of unsupported sleepers, the wheel/rail contact force would increase as well. It is worth mentioning that increasing the velocity in unsupported sleepers less than 4, does not have such an effect, but, in more than 4 unsupported sleepers, the maximum displacement of rail increase as the velocity increases. The deal of increase in wheel/rail contact force in this case when the track possesses one and six unsupported sleepers is, respectively, 12.37% and 87.62% larger for speed of 110 km/h in comparison with speed of 10 km/h.

Also, Fig. 8 shows the changes of wheel/rail contact force on

a track with one unsupported sleeper. As it could be observed, as the velocity of the locomotive increases from 20 km/h to 110 km/h, the changes of wheel/rail contact force in the area with unsupported sleeper increases.

Moreover, when the vehicle enters the unsupported area, the wheel/rail contact force initially decreases, then increases, and decreases again. The first decrease in contact force is due to rail deformation in unsupported area. The increasing of contact force is owing to wheel passing while pulling out of the unsupported area. The reason of second decrease is that the increasing in contact force in previous step causes the wheel towards lifting, makes a second decrease in contact force.

7- Conclusion

In this study, the effect of vehicle velocity on the displacement of rail has been dealt with. Track displacement that occurs owing to unsupported region causes the wheel/rail contact force in the

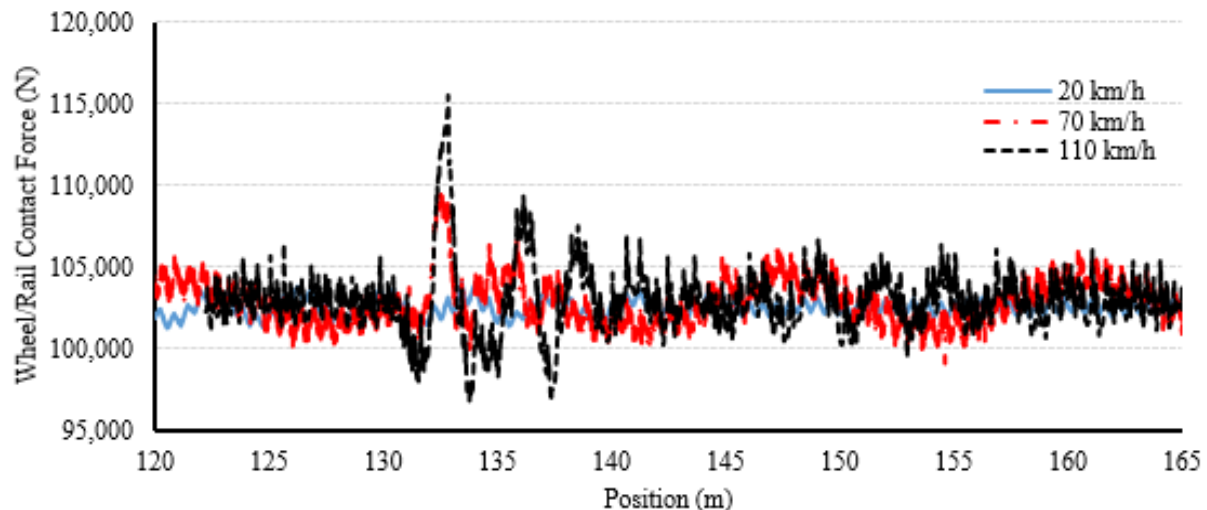


Fig. 8. Wheel/rail contact force through unsupported sleeper region.

unsupported area becomes higher. To prevent such a defect it is needed to perform periodic observations and data extraction of measuring machines for track displacement measurements.

In order for modeling a flexible track with unsupported sleeper and with multibody vehicle, SIMPACK program has been used. By using the connection between ANSYS and SIMPACK programs it would be possible that the model of flexible track be modeled in the environment of multibody program. The results of numerical simulation were verified with the results of field test and the results obtained from numerical simulation have a good agreement with the results of field test. By studying the results obtained from numerical simulation, it could be observed that the displacement of a track with unsupported sleepers under the effect of vehicle velocity has different results. When the ballasted track has less than 4 unsupported sleepers, the velocity of the vehicle has no effect on the displacement, but if unsupported sleepers are more than 4, the effect of vehicle velocity would be considerable.

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