Geomechanics and Engineering, *Vol. 32, No. 5 (2023) 483-494*
https://doi.org/10.12989/gae.2023.32.5.483

Three-dimensional finite element analysis of the interference of adjacent moving trains resting on a ballasted railway track system

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(*Received October 31, 2022, Revised February 1, 2023, Accepted February 7, 2023*)

Abstract. High-speed trains became common nowadays due to the need for fast and safe mean to transport goods and people. However, the use of high-speed trains necessitates the examination of the critical speed, which is the train speed at which the maximum settlement of the railway track occurs. The critical speed and railway track settlement have been investigated considering only one train in previous studies. However, it is normal to have two adjacent trains moving at the same time. This paper aims to understand how the interference of two moving trains affects the settlement and critical speed of ballasted railway track. Calibrated three-dimensional finite element models of railway track subjected to one moving train and two moving trains have been developed to address the aim of the study. It is found that the interference dramatically increases the railway track settlement with a percentage increase ranges between 5 and 100%. It is also found that the percentage increase of the railway track settlement depends on the train speed and the distance between the moving trains. In addition, it is found that the thickness of the ballast layer and the stiffness of the subgrade have minor influence on the percentage increase of the settlement. Importantly, the results of this paper illustrate the importance of the interference of the moving trains on the dynamic response of the railway track. Thus, there is a need to consider the dynamic interaction between the adjacent moving trains in the design of railway track foundation.

Keywords: critical speed; interference effect; moving trains; railway track settlement

1. Introduction

Many countries throughout the world have seen fast developments in high-speed railway systems in the last two decades due to the need for a transportation mean that is safe and economic (Li *et al.* 2015, Shih *et al.* 2017, Mosayebi *et al.* 2017, Ramil, 2021, Fern´andez-Ruiz *et al.* 2021, Sadeghi *et al.* 2021, Jiang *et al.* 2022). For example, the Japanese trains administration built the Shinkansen HST network, which travels at a speed of 320 km/h. In addition, there are attempts in China to increase the train speed to 400 km/hr (Sayeed and Shahin 2016a). However, the frequency of vibration of high-speed trains causes strong amplifications of acceleration (Alves Costa *et al.* 2015, Kaynia *et al.* 2000, Krylov 2001, Sayeed and Shahin 2016b) and could cause catastrophic effects similar to the effect of earthquakes reported in many previous studies (Minaie and Moon 2017, Argyroudis *et al.* 2019, Chen *et al.* 2019, Forcellini 2020, Han *et al.* 2022). These amplifications produced new challenges and concerns regarding the performance of railway track foundations (Sayeed and Shahin 2016b). The risk on the railway track increases when the speed of the train becomes equal or nearly equal to the shear wave velocity of the ground, especially for soft subgrade, because it will cause a large settlement, and hence catastrophic failure. This speed is known as the critical speed. Thus, many studies have been conducted on the response of railway track subjected to train loads to investigate the critical speed and the settlement of the railway track. These studies considered a single cyclic or moving point load rather than the genuine (dynamic) train movement loads to study the effect of train speed on the performance of the railway track (Sayeed and Shahin 2016b). However, the assumption of a single cyclic or moving wheel load is very uncertain because the dynamic amplification and critical speed depend on the wavelength of the soil, and the distance between the axles of the train (Kaynia *et al.* 2000, Sayeed and Shahin 2016b).

Madshus and Kaynia (2000) investigated the behavior of soft soil under the effect of one X2000 HST moving train. They found that the factors which control the critical speed are the Rayleigh wave, the embankment properties, and the distances between the train loads (i.e., axles). Gao *et al.* (2012) developed two and half (2.5D) finite element model to study the dynamic response of railway track resting on multi layered saturated soil and subjected to high-speed moving trains. Hu *et al.* (2016) studied the dynamic response of subgrade subjected to moving load using 2.5D finite element analysis. They considered a speed range of 50 to 200 m/sec. They noticed that the critical speed of the train is always higher than the Rayleigh wave velocity of the ground (subgrade). Sayeed and Shahin (2016a) investigated the dynamic response of railway track subjected to one moving train using three-dimensional finite element analysis. They studied the effect of the train speed,

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http://www.techno-press.org/?journal=gae&subpage=7

ISSN: 2005-307X (Print), 2092-6219 (Online)

stiffness of the subgrade, thickness of the ballast layer, and the amplitude of train loads on the critical speed. Hu *et al.* (2018) developed a 2.5D finite element model to study the critical speed for ballastless railway track system subjected to one moving train. They conducted a parametric study to find the critical speed and discussed the behavior of a ballastless railway track system under various train speeds.

Shahraki (2019) studied the effect of stone column reinforcement of the subgrade on the settlement of a railway track subjected to one moving train. Fern´andez-Ruiz *et al.* (2021) studied the possibility of improving the critical speed of a ballasted railway track under the effect of one moving train using stone column technique. They studied two cases: the first case was for the subgrade without reinforcement and the second case was subgrade with stone column reinforcement. The results illustrated the influence of the stone columns reinforcement on the railway track settlement, dynamic amplification factor, and critical speed. In addition, the results showed that the depth of the stone columns dramatically influenced the produced settlement, and hence the critical speed. Wang *et al.* (2021) examined the settlement of loess soil due to the effect of one moving train. Alzabeebee (2022a) proposed a methodology to produce a calibrated three-dimensional finite element model to predict the settlement of one moving train using Plaxis 3D. Malmborg *et al.* (2022) examined the effectiveness of increasing the stiffness of part of the subgrade soil on the critical speed using 2.5D finite element analysis. They found that increasing the stiffness of the subgrade soil at shallow depth increased the critical speed. Hadi and Alzabeebee (2022) conducted a sensitivity analysis to examine the influence of the finite element model width, mesh density, and time step on the accuracy of the 3D finite element analysis of the settlement of the railway track subjected to two adjacent moving trains.

It is evident based on this review that there are limited studies on the effect of the embankment thickness and subgrade stiffness on the dynamic settlement and critical speed of railway track subjected to one moving train. In addition, there is no study that concerned with the effect of the dynamic interference of two adjacent moving trains on the railway track settlement and critical speed, although it is not uncommon to have two adjacent trains moving at the same time bearing in mind that recent studies demonstrated the remarkable effect of the dynamic interference on the settlement of the ground (Alzabeebee 2020a). To fill this gap, this study aims to understand how the dynamic interference influences the dynamic response and settlement of railway track. To address this aim, this paper concerns with the following objectives:

- Develop a three-dimensional finite element model to simulate the dynamic response of railway track.
-Study the effect of train speed, thickness of embankment layer, and stiffness of the subgrade soil on the dynamic response of a railway track subjected to loads of one moving train.
- Study the effect of the dynamic interference of two-moving trains travelling at the same time and in the same direction on the dynamic response of two adjacent railway tracks.
- Study the effect of the thickness of the embankment and stiffness of the subgrade layer on the dynamic response and the critical speed of two adjacent railway tracks

2. Methodology of the analysis

2.1 Description of the developed finite element model

As stated in Section 1, this study examines the effect of the interference of two trains travelling at the same time and in the same direction. Thus, a three-dimensional finite element model has been developed to model this problem using PLAXIS 3D software to guarantee accurate analysis of the of railway track under the effect of the moving train loads. The time history analysis finite element analysis is conducted using Eq. (1) (Alzabeebee 2020b, Alzabeebee 2022a, b)

$$M\ddot{u} + C\dot{u} + Ku = F \tag{1}$$

Where, $[M]$ is the mass matrix, $[\ddot{u}]$ is the acceleration, $[C]$ is the damping matrix, $[\dot{u}]$ is the velocity, $[K]$ is the stiffness matrix, $[u]$ is the displacement, and $[F]$ is the applied load.

The dimensions and configuration of the developed numerical model is shown in Fig. 1. As shown in Fig. 1, the model is built with a length, width, and height of 180 m, 100 m, and 30 m. The width of the model (180 m) has been determined based on a sensitivity study considering two adjacent moving trains spaced at a distance of 10 m (which is the maximum spacing between the trains that is considered in this study). The results of the sensitivity study are discussed in another publication by the authors (please refer to Hadi and Alzabeebee (2022) for further details). The length (100 m) has been proposed based on the distances between the loads of one train to ensure that there is enough length to enable the consideration of all of the moving loads together in the analysis. In addition, the model height (30 m) is determined based on the depth of soil deposit on top of the rock in Al-Diwaniyah city (Alzabeebee 2022).

The standard boundary conditions for the static analysis have been employed similar to many previous studies in the literature (Lv *et al*. 2014, Hasan 2013, Mandeel *et al*. 2020, Zhang *et al*. 2021, Forcellini and Alzabeebee 2022, Jiang *et al*. 2022, Wang *et al*. 2022, Al-Jeznawi *et al*. 2023). The bottom of the model has been fixed so that it is not allowed to move in any direction, while the model sides have been permitted to move in the vertical direction and restrained in other directions. In addition, the absorbent boundaries have been applied at the bottom and the sides of the model to eliminate inaccuracy in the analysis which is associated with wave reflection (Alzabeebee *et al*. 2018, 2022, Khan and Dasaka 2020a, b, c, 2022, Moghadam and Ashtari 2020, Chango *et al*. 2022). The Lysmer and Kuhlemeyer (1969) absorbent boundaries are employed in the dynamic analysis stage. The formulation of these absorbent boundaries is shown in Eqs. (2) and (3).

$$\sigma_n = -C_1 V_p p \dot{u}_x \tag{2}$$

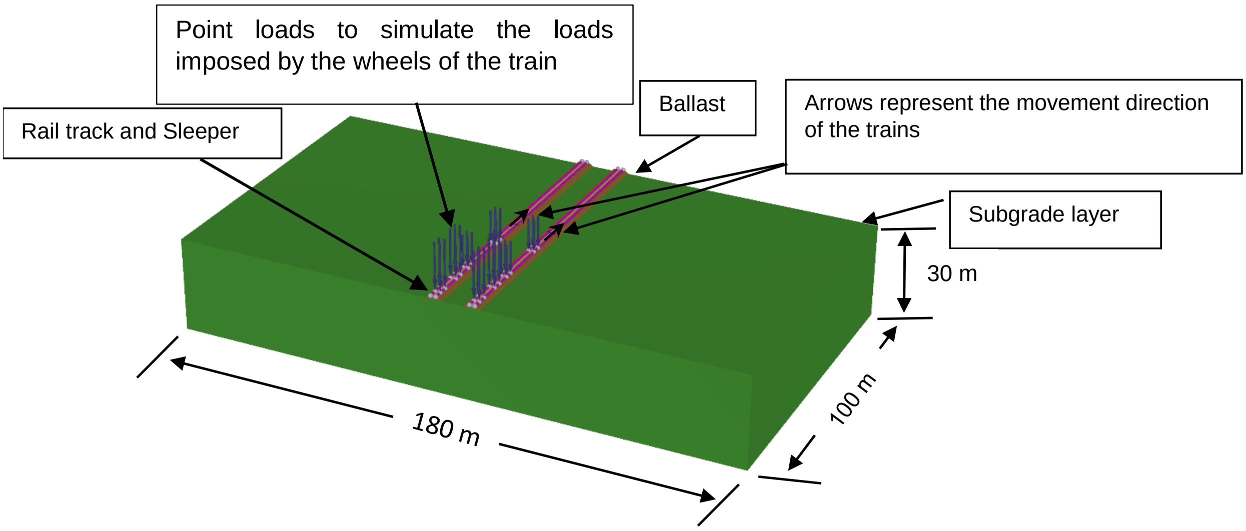


Fig. 1 The geometry of the finite element model of the railway tracks subjected to two adjacent moving train loads

$$\tau = -C_2 V_s p \dot{u}_y \tag{3}$$

Where, σ_n is the normal stress, Coefficients C_1 and C_2 are usually referred to as relaxation coefficient and have been set equal to 1.0 in accordance with the recommendation of Plaxis manual (Alzabeebee 2022). $\dot{u}_x$ and $\dot{u}_y$are velocities in horizontal and vertical directions, V_p is the pressure wave velocity, V_s is the shear wave velocity and τ is the shear stress.

10-nodded solid elements have been used to model the sleepers, embankment, and subgrade soil. The embankment consists of a ballast layer with a sloping angle of 45°. In addition, one dimensional beam elements have been used to simulate the rails. Furthermore, the train loads have been simulated as point load with the movement option available in Plaxis 3D (Alzabeebee 2022). This technique enables the simulation of the movement of the train considering a speed that is set during the modelling stage. The geometry of the trains will be discussed in the next subsection. It is worthy to state that modelling moving train loads as moving point loads is common in the simulation of moving trains on railway track (Mellat *et al.* 2014, Alzabeebee *et al.* 2018, 2023, Sayeed and Shahin 2016a, b, 2018a, b, 2022).

Very fine mesh has been used in the analysis based on a sensitivity analysis conducted to check mesh convergence (please refer to Had and Alzabeebee (2020) for the results of the sensitivity analysis). In addition, the swept mesh option available in Plaxis 3D is used to ensure symmetrical mesh for the two railway tracks, which enables robust results and overcome issues of unstructured mesh configuration. The mesh for a selected scenario (spacing between trains (S) = 10 m and thickness of embankment = 0.5 m) is presented in Fig. 2. In addition, a time step of 0.01 Sec has been set in this stage. This time step has been considered appropriate after a sensitivity analysis using different speeds and for different mesh sizes based on the methodology proposed by Alzabeebee (2022). The results of the sensitivity analysis are presented in Hadi and Alzabeebee (2022).

It is important to state that it was not possible to compare the results of the developed model with any experimental work as there is not study that has been conducted on the settlement of the railway track under the effect of two adjacent moving trains. However, the authors carried out a calibration study in which the effect of model width, thickness of soil deposit, mesh density, and time step were examined (Hadi and Alzabeebee 2022). In this way, the authors ensured that the developed model is valid, and its results are not affected by the mesh size, finite element model dimensions, and time step. In addition, the numerical model is built based on the experience of modelling this problem gained from many previous studies which have studied the dynamic response of railway track subjected to moving trains (Hall 2000, Holm and Riis 2014, Mellat *et al.* 2014, Fern´andez-Ruiz *et al.* 2021, Sayeed and Shahin 2016a, b, 2018a, b, 2022) and also based on the experience of the co-author in modelling the effect of train moving load on soil and buried structures (Alzabeebee *et al.* 2018). Furthermore, the moving load is simulated using moving train function available in Plaxis and this function has been validated using many previous studies (e.g., Fern´andez-Ruiz *et al.* 2021). Finally, the dynamic analysis methodology has been verified against results of the wave propagation solution of half space proposed by Foinquinos and Roesset (2000). However, this verification has not been included in the paper for the sake of briefing.

2.2 Constitutive models used for railway, sleepers, embankment, and soil

The embankment has been modelled using bi linear elastic-plastic material with the Mohr-Coulomb failure criteria to provide better accuracy of analysis. However, the linear elastic model is used to simulate the behavior of the subgrade soil to avoid unnecessary iterations in the analysis, bearing in mind that using the elastic perfectly plastic model for the subgrade does not enhance the accuracy of the analysis as noted by the authors. In addition, many

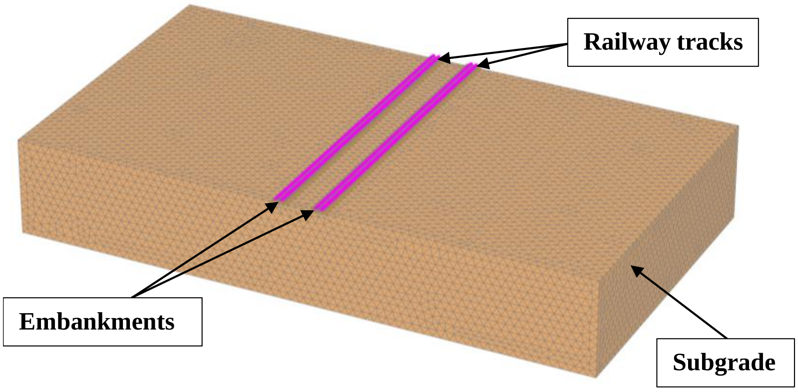


Fig. 2 Finite element mesh for a selected scenario

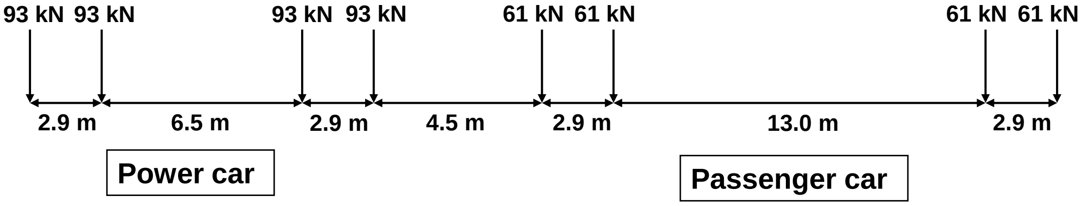


Fig. 3 Loading configuration and wheel's load of X 2000 train (Hall 2000)

Table 1 Parameters of the subgrade soil, ballast, and sleepers

Material	γ (kN/m^3)	E (MPa)	υ	c' (kPa)	$\o'$	φ	α (s^{-1})	β (s)
Subgrade (soft soil)	18.5	16	0.25	---	---	---	0.2454	0.00160
Ballast	17.0	134	0.30	20	48	18	2.3800	0.00100
Sleepers	23.5	25,500	0.20	---	---	-	0.3900	0.00016

Table 2 Properties of the rail track

γ (kN/m^3)	E (MPa)	Area	I_2	I_3
77.0	206,000	7.670×10^{-3}	0.03038×10^{-3}	0.03038×10^{-3}

studies have used the linear elastic model to model the subgrade for the case of a moving train (Sayeed and Shahin 2016a, b, 2018a, b, 2022, Malmborg *et al.* 2022, Jiang *et al.* 2022). The concrete sleepers and the rail track have been simulated using the linear elastic model. The properties of the embankment, subgrade, and sleepers have been taken from relevant studies in the literature (Li *et al.* 2018, Sayeed and Shahin 2016a, Xin *et al.* 2021). Table 1 shows the parameters adopted for the subgrade, embankment, and sleepers. It is worthy to state that the soft subgrade soil is initially adopted as can be noticed in Table 1. However, the stiffness of the subgrade (E) is changed in the parametric study to address the objectives of the papers as will be explained further in Sections 3 and 4. A section type of UIC-60 has been considered in the simulation of the rail track. Table 2 presents the parameters adopted for the UIC-60 section (Sayeed and Shahin 2018a). It is worthy to stress that the effect of the compaction on the ballast layer is implicitly included as the properties of the compacted ballast are considered in the analysis.

2.3 Train geometry

In this study, the passenger train type X-2000 has been used in the analysis (Hall 2000). Only the power and the passenger cars are modeled in this study to reduce the finite element model length and hence, the computational time. However, these cars include the heaviest axles of this train type to ensure the consideration of the stringent condition for this train type. The loading configuration and wheel's loads of the power and passenger cars of this train are shown in Fig. 3 (Hall 2000).

3. Dynamic response of the railway track under the loads of one train

The case of a railway track subjected to the loads of one train has been studied first to understand the effect of the train speed, subgrade stiffness, and thickness of the ballast layer (embankment) on the settlement of the railway track. For this purpose, the same methodology (assumptions, finite element model dimensions, boundary conditions, constitutive models, and loading configuration) discussed in the previous section has been used to develop a model for the case of railway track subjected to one moving train. This model is presented in Fig. 4.

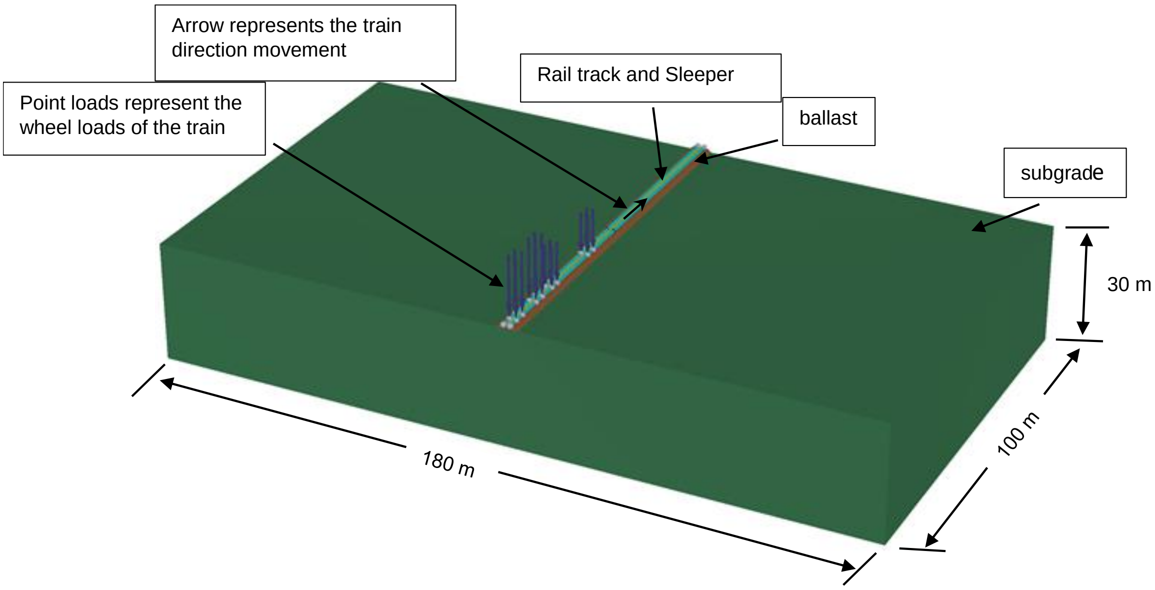


Fig. 4 The finite element model of railway track subjected to one moving train

3.1 Effect of train speed and subgrade stiffness of the subgrade

The effect of train speed has been investigated with a speed range of 25 km/hr to 450 km/hr for different values of subgrade stiffness (8 MPa, 16 MPa, and 32 MPa). An embankment thickness of 0.5 m has been considered in the analyses. Figs. 5(a)-5(j) show the results of the settlement-time relationship of the railway track for a train speed of 25 km/hr, 50 km/hr, 100 km/hr, 150 km/hr, 200 km/hr, 250 km/hr, 300 km/hr, 350 km/hr, 400 km/hr, and 450 km/hr, respectively, for the aforementioned subgrade stiffnesses. It is obvious that, as expected, the settlement reduces as the subgrade stiffness increases. In addition, it is also clear from the figures that the stiffness of the subgrade does not impact the trend of the settlement-time relationship. However, it is also clear that the speed of the train has a remarkable influence on the maximum settlement of the railway track.

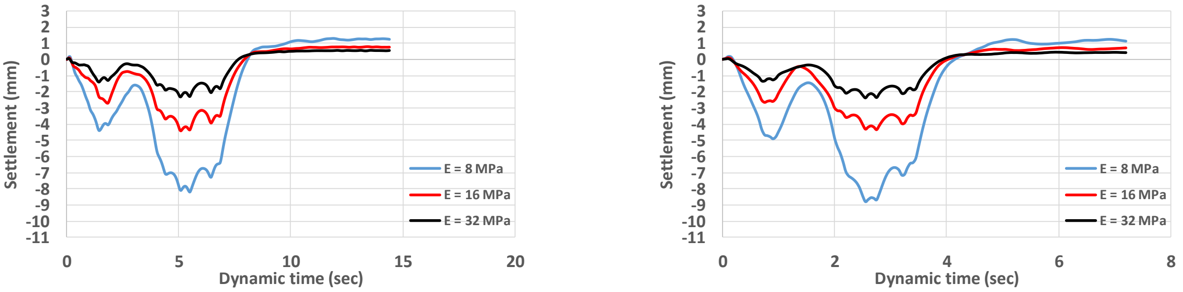
Fig. 6 presents the relationship between the maximum settlement and the train speed to illustrate the effect of the train speed on the maximum settlement. It is clear from Figure 6 that for subgrade stiffness of 8 MPa, the settlement rises as the speed increases up to 200 km/hr then declines as the speed further increases. Thus, it can be said that the critical speed is equal to 200 km/hr for a subgrade stiffness of 8 MPa. In addition, the increase of the settlement as the train speed rises is less pronounced when the subgrade stiffness becomes 16 MPa, but it is also occurred at a train speed of 200 km/hr. On the other hand, the effect of the train speed on the railway track settlement is not pronounced for subgrade stiffness of 32 MPa and it is occurred at train speed of 250 km/hr.

3.2 Effect of ballast thickness (embankment)

The effect of the ballast layer thickness (H) has been examined by considering two additional thicknesses (0.75 m and 1.00 m) in addition to the thickness of 0.50 m (which has been discussed in the previous subsection) to understand how the thickness of the ballast layer (embankment) influences the railway track settlement and thus the critical speed. The analyses in this section have been conducted for a train speed range of 25 km/hr to 450 km/hr. Figs. 7-9 show the effect of ballast thickness on the relationship between the train speed and the maximum settlement of the railway track for subgrade stiffness of 8 MPa, 16 MPa, and 32 MPa, respectively. It is evident from Figs. 7-9 that, in general, increasing the thickness of the ballast layer reduces the maximum railway settlement. The percentage decrease of the maximum settlement ranges between 3 to 11% for a subgrade stiffness of 8 MPa, while it ranges between 1 to 10% for a subgrade stiffness of 16 MPa. Finally, the percentage decrease ranges between 1 to 6% for a subgrade stiffness of 32 MPa. It is evident based on the calculated percentages that the ballast thickness has minor influence on the settlement and reduces it with small percentage which ranges between 1 to 11%. This behavior is due to the effect of the stiffness of the embankment in amplifying the vibration effect (i.e., the acceleration). Hence, although the use of higher embankment thickness reduces the load on the soft ground, but it also amplifies the vibration. It can also be stated, based on the results of Figs. 7-9, that increasing the thickness of the ballast layer does not change the critical speed.

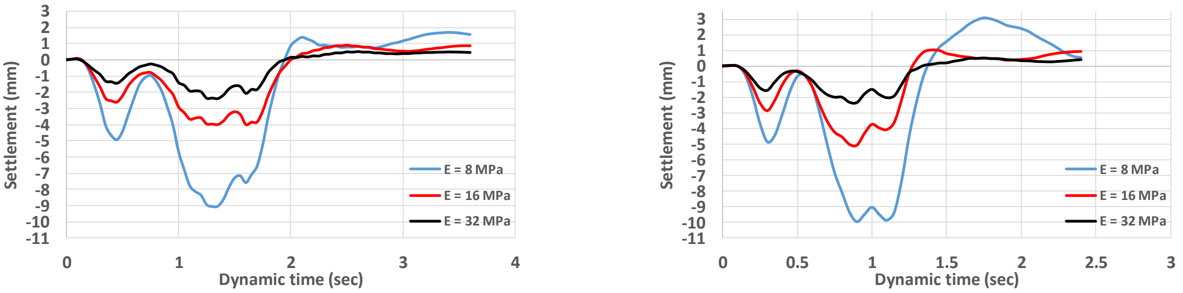
4. Interference effect on the dynamic response of the railway tracks

The effect of the interference of the two trains is examined in this section. Hence, different scenarios of trains moving at the same time and in the same direction have been studied, where the effect of the distance between the two railway tracks is examined for different train speeds, ballast layer thicknesses, and subgrade stiffnesses.



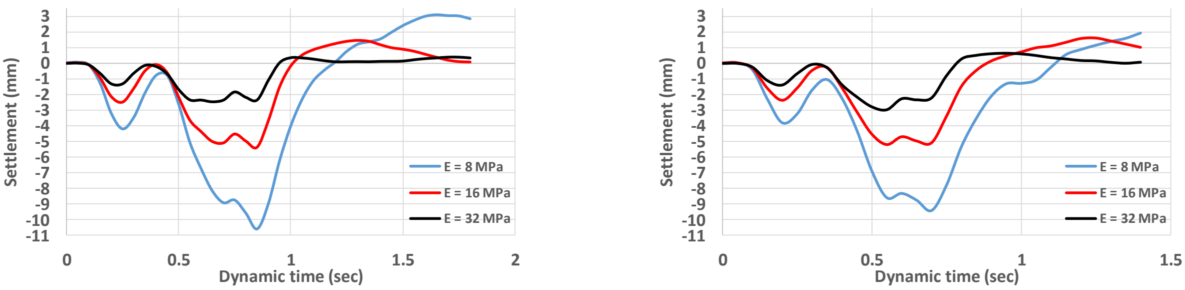
a) Speed = 25 km/hr

b) Speed = 50 km/hr



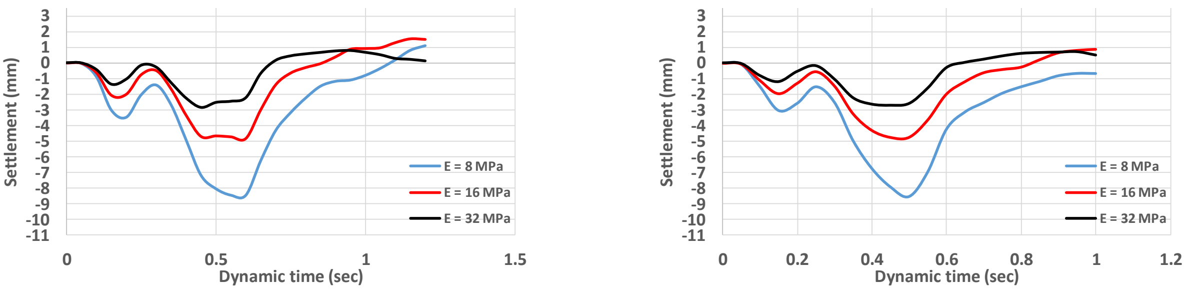
c) Speed = 100 km/hr

d) Speed = 150 km/hr



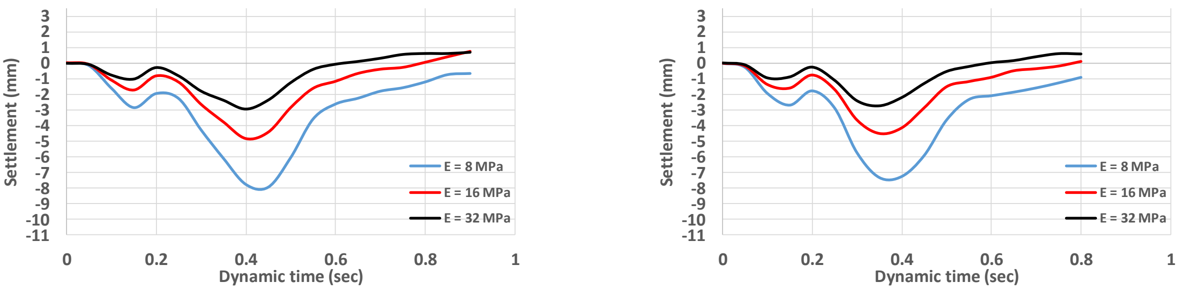
e) Speed = 200 km/hr

f) Speed = 250 km/hr



g) Speed = 300 km/hr

h) Speed = 350 km/hr



i) Speed = 400 km/hr

j) Speed = 450 km/hr

Fig. 5 Effect of train speed and subgrade stiffness on the vertical displacement of the railway track under one train loads

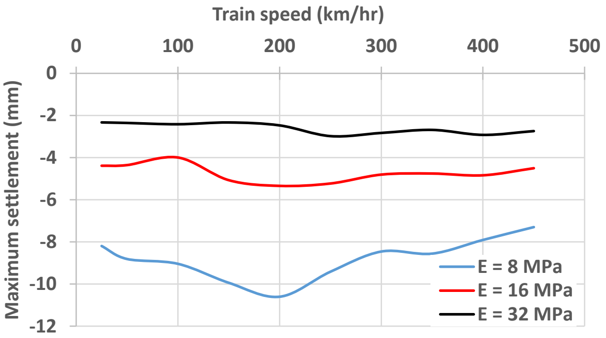


Fig. 6 Effect of the train speed and subgrade stiffness of the subgrade on the maximum settlement

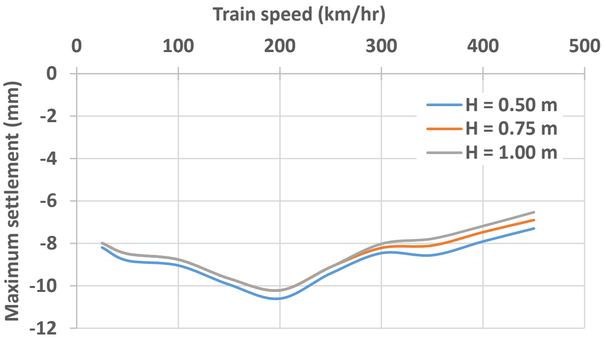


Fig. 7 Effect of the ballast thickness on the maximum railway track settlement for a subgrade stiffness of 8 MPa

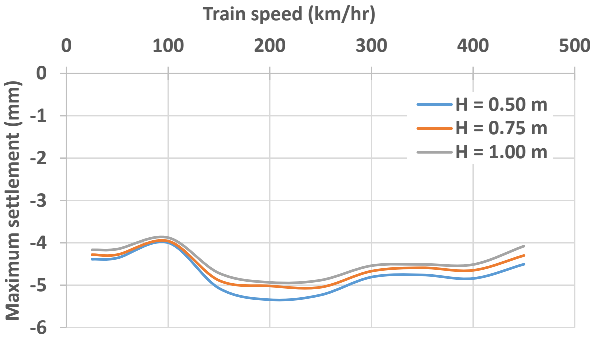


Fig. 8 Effect of the ballast thickness on the maximum railway track settlement for a subgrade stiffness of 16 MPa

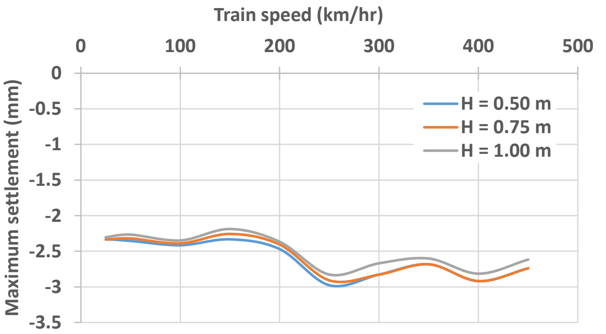


Fig. 9 Effect of the ballast thickness on the maximum railway track settlement for a subgrade stiffness of 32 MPa

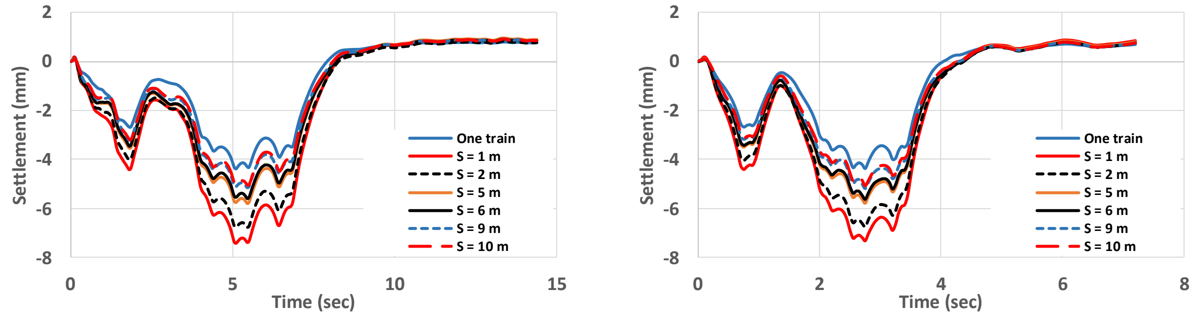
The two adjacent trains are assumed to move at the same speed to simplify the analysis. In total, 540 scenarios have been examined in this section. This means that 540 3D finite element models have been built, analyzed and post processed in this section. Different values for the distance between the two trains (i.e., two railway tracks) (S) have been considered to allow an insight into the effect of S on the railway track settlement and the critical speed. The S values considered in the analyses are equal to 1 m, 2 m, 5 m, 6 m, 9 m, and 10 m. These values have been selected to show how the distance between the two trains affects the results. In addition, a ballast thickness of 0.50 m, 0.75 m, and 1.00 m and subgrade stiffness of 8 MPa, 16 MPa, and 32 MPa have also been considered to study the sensitivity of the effect of the subgrade stiffness and ballast thickness on the interference of the trains. Thus, this section is separated into three subsections to allow better presentation and discussion of the obtained results.

4.1 Effect of distance between the two trains (S)

Figs. 10(a)-10(j) compare the relationship of settlement of the railway track and time for different train speeds for two adjacent trains moving at a speed range of 25 km/hr to 450 km/hr. The settlement of the railway track for the case of one moving train is also presented in Figs. 10(a)-10(j) for the sake of comparison. These figures are for the case of thickness of ballast layer of 0.5 m and subgrade stiffness of 16 MPa. It is evident from the figures that the interference remarkably increases the settlement of the railway track. This behavior is due to increasing the vibration sources (Alzabeebee 2020). However, the interference does not influence the trend of the relationship of the settlement and time.

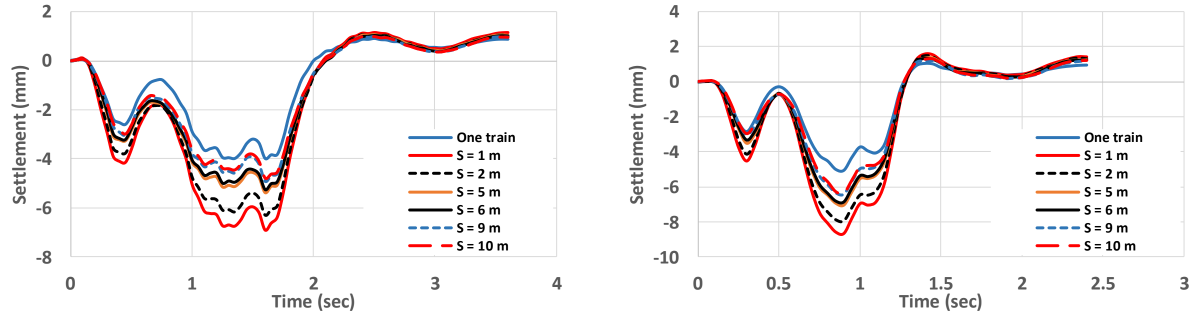
Fig. 11 presents the effect of the interference on the maximum settlement of the railway track for the case of one moving train and two adjacent moving trains to carefully examine the effect of the interference on the critical speed. It is evident from the figure that the interference does not influence the trend of the relationship between the maximum settlement of the railway track and the train speed. However, it is also clear that the settlement remarkably rises for the case of S = 1 m and then declines gradually as the distance between the moving trains (S) increases. In addition, it is evident from the figure that the effect of the interference is also existed even for S = 10 m.

Fig. 12 presents the ratio of the settlement of the railway track for the case of two adjacent moving trains to the corresponding settlement for the case of one moving train. This figure presents the effect of the interference in a better way, and it is clear from this figure that the maximum increase in the settlement occurs at a train speed of 300 km/hr for all of the values of S except the case of S = 9 m. In addition, the figure shows the percentage increase of the settlement, where it is clear that the percentage increase of the settlement for the case of S = 1 m ranges between 69% to 84%. On average, the percentage increase of the settlement is equal to 72%, 59%, 38%, 34%, 22% and 20 % for S of 1 m, 2 m, 5 m, 6 m, 9 m and 10 m, respectively.



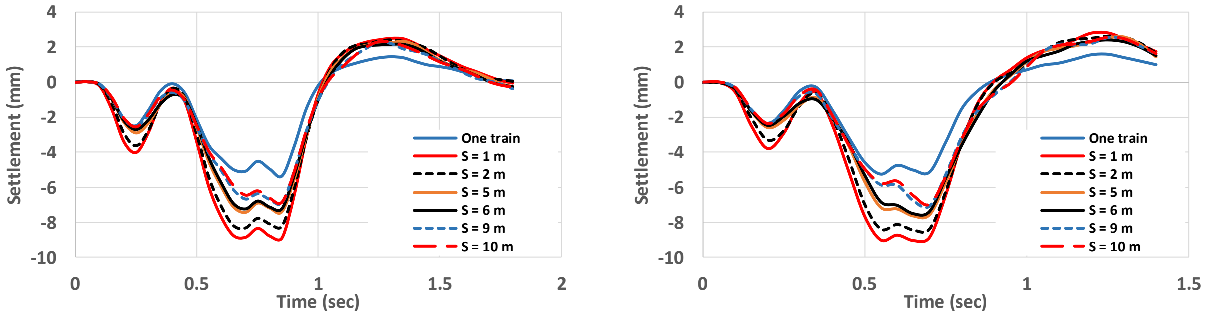
a) Train speed = 25 km/hr

b) Train speed = 50 km/hr



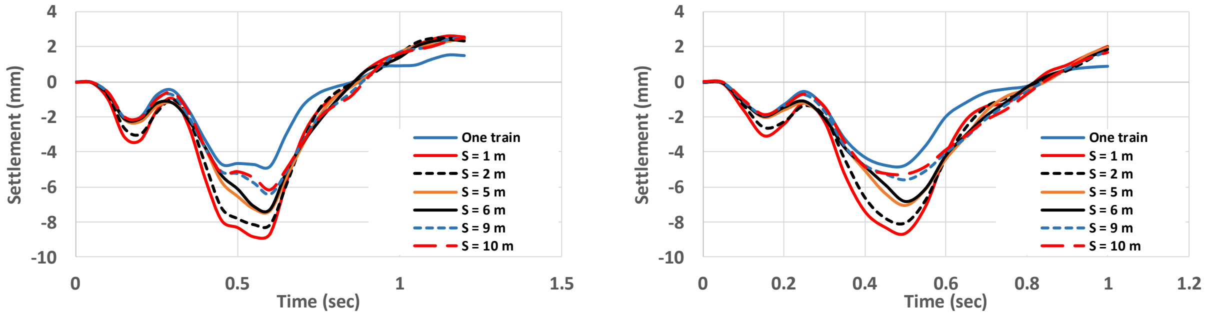
c) Train speed = 100 km/hr

d) Train speed = 150 km/hr



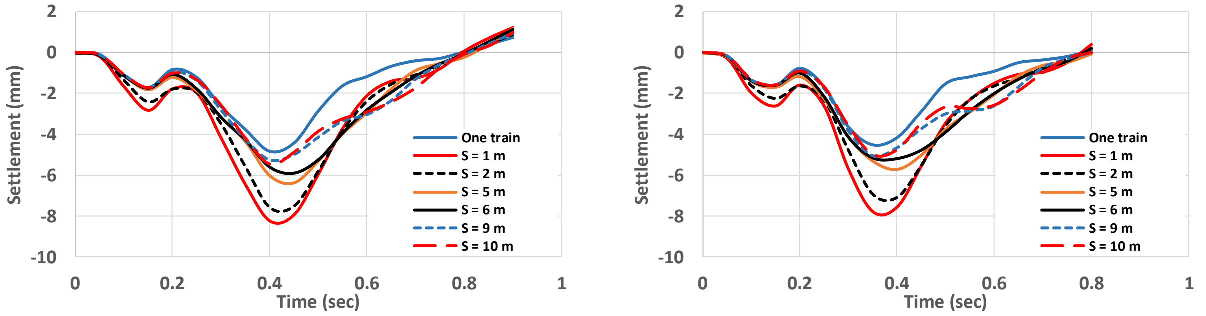
e) Train speed = 200 km/hr

f) Train speed = 250 km/hr



g) Train speed = 300 km/hr

h) Train speed = 350 km/hr



i) Train speed = 400 km/hr

j) Train speed = 450 km/hr

Fig. 10 Relationship between time and railway track settlement for one and two adjacent moving trains

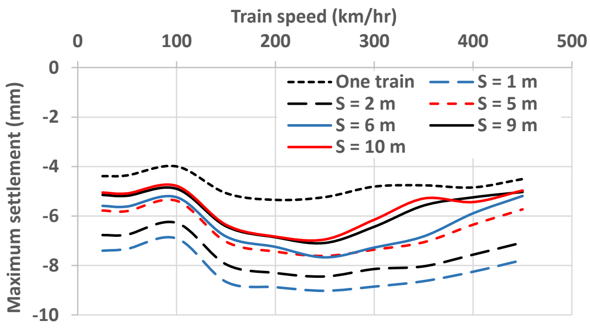


Fig. 11 The effect of the distance between the two trains (S) on the maximum settlement of the railway track for the case of a thickness of ballast layer of 0.5 m and subgrade stiffness of 16 MPa

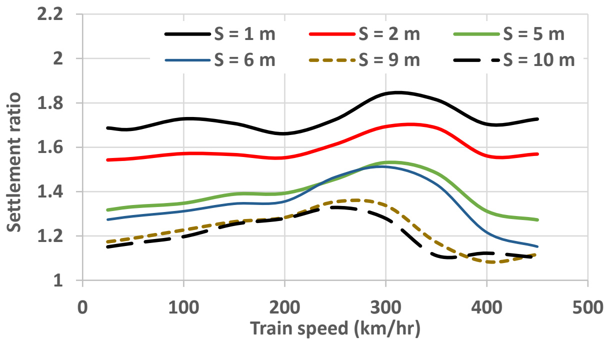


Fig. 12 The settlement ratio for the case of a thickness of ballast layer of 0.5 m and subgrade stiffness of 16 MPa

4.2 Effect of ballast thickness on the dynamic interference

Figs.13-15 present the effect of the ballast thickness on the relationship between settlement ratio and train speed for S of 1 m, 5 m and 10 m, respectively and for subgrade stiffness of 8 MPa. It is evident from the figures that, in general, the settlement ratio is not noticeably influenced by the ballast thickness. This is due to the fact that the effect of the ballast thickness on the railway track settlement is minor as discussed for the case of one train. In addition, it is difficult based on the results of Figs. 13-15 to generalize a trend for the effect of the ballast thickness, which is due to the limited effect of this parameter on the railway track settlement and also due to the effect of the vibration of the trains which makes the problem more complicated.

4.3 Effect of subgrade stiffness on the dynamic interference

Figs. 16-18 present the effect of the subgrade stiffness for the case of a thickness of ballast layer of 0.50 m and S of 1 m, 5 m, and 10 m, respectively. It is evident from the figures that the effect of the subgrade stiffness on the settlement ratio is random and cannot be generalized in a defined trend. This is due to the effect of the subgrade stiffness and the interference on the dynamic amplification and the fact that the settlement ratio is derived using results of the settlement of railway track settlement of one and two moving trains.

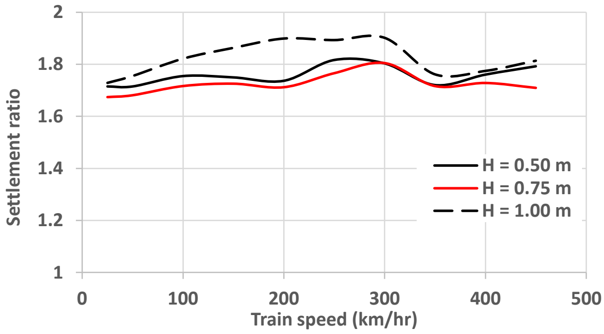


Fig. 13 Effect of the thickness of the ballast layer on the settlement ratio for the case of subgrade stiffness of 8 MPa and spacing between trains of 1 m

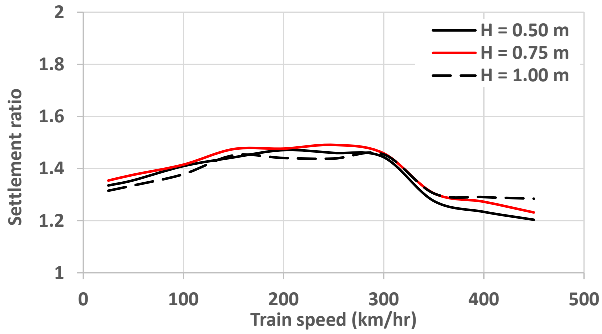


Fig. 14 Effect of the thickness of the ballast layer on the settlement ratio for the case of subgrade stiffness of 8 MPa and spacing between trains of 5 m

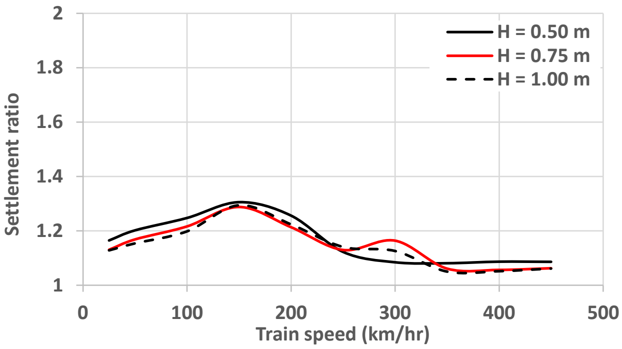


Fig. 15 Effect of the thickness of the ballast layer on the settlement ratio for the case of subgrade stiffness of 8 MPa and spacing between trains of 10 m

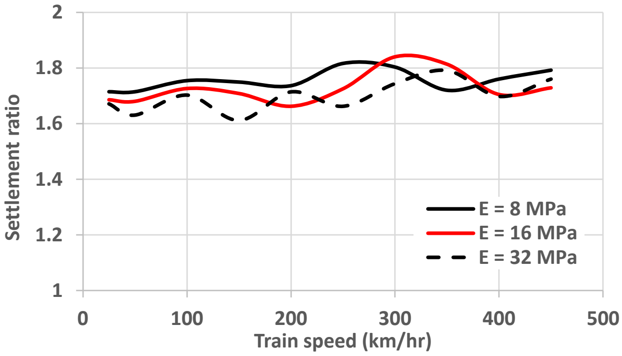


Fig. 16 Effect of the subgrade stiffness for the case of ballast thickness of 0.50 m and S of 1 m

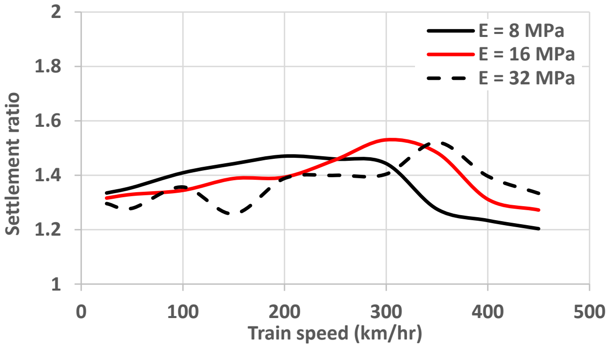


Fig. 17 Effect of the subgrade stiffness for the case of ballast thickness of 0.50 m and S of 5 m

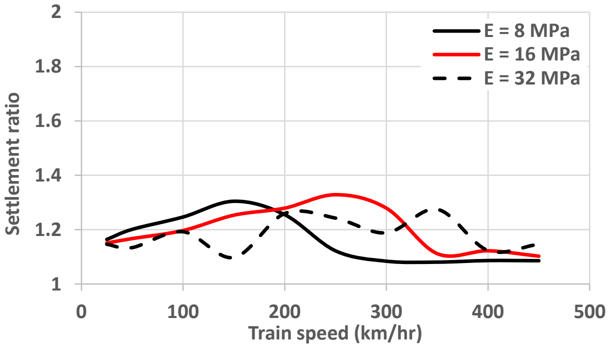


Fig. 18 Effect of the subgrade stiffness for the case of ballast thickness of 0.50 m and S of 10 m

5. Conclusions

This paper examined the effect of the interference of two moving trains on the dynamic response of a railway track using calibrated three-dimensional finite element model. The cases of one moving train and two adjacent moving trains spaced at a distance S have been considered to provide a comprehensive understanding of the interference effect. Based on the post processing of the results of the models, it is possible to state the following conclusions:

1- Increasing the subgrade stiffness reduces the sensitivity of the railway track settlement to the train speed. In addition, the critical speed increases as the subgrade stiffness increases.

2- Increasing the thickness of the ballast layer slightly decreases the maximum settlement of the railway track with a percentage decrease ranging between 1 and 11% depending on the speed of the train, thickness of the ballast layer, and stiffness of the subgrade soil. In addition, changing the ballast layer thickness does not influence the critical speed.

3- The interference remarkably increases the settlement of the railway track. In addition, the effect of the interfence increases as the distances between the two trains decreases.

4- The interfence does not change the value of the critical speed.

5- The interference effect on the railway track settlement is pronounced even for the case of distance between the two trains (S) = 10 m, where the increase in the settlement of the train for S = 10 m ranged between 5 and 33%.

6- Changing the ballast thickness has minor influence on the settlement ratio. In addition, this minor influence cannot be generalized in a general trend for different S values due to the complexity of the interaction of the vibration effect with the stress attenuation caused by the increase of the ballast layer thickness.

7- In general, the effect of the subgrade stiffness on the dynamic interference is not remarkable and it cannot be generalized in an obvious trend. This is due to the complexity of the relationship and the effect of vibration.

8- Importantly, the study illustrated the dramatic influence of the interference on the settlement of the railway track. Thus, it is necessary to consider this effect in future designs and in the calculation of the critical speed.

Acknowledgements

This work was supported by the Thailand Science Research and Innovation Fundamental Fund fiscal year 2023.

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