Journal of Engineering and Applied Science Vol. 5, No. 1, pp. 41-52, June 2021

Journal of Engineering and Applied Science

Contents are available at www.jeas.ruet.ac.bd

Dynamic Behaviours of Geocell Reinforced Ballasted Railway Track Subjected to Train Moving Loads

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ARTICLE INFORMATION

Received date : 20 Jan 2021
Revised date : 21 May 2021
Accepted date : 28 May 2021

Keywords

Ballasted railway track
Finite element modelling
Train moving loads
Geocell
Track-ground response

ABSTRACT

The railway network plays a very important role among different modes of public transportation in terms of safety, carrying capacity, speed and cost. In the railway track-ground system, the train moving loads generate large vibrations, especially when the track built on soft subgrade, which increases the risk of track damages and train derailment. In order to increase track support capacity and thereby decrease the track operation and maintenance costs, track stabilization can be an important option. To stabilize the ballasted railway track, geocell reinforcement may be placed inside or below the ballast or subballast layers. In the current paper, a classy three-dimensional finite element model of ballasted railway track is developed to investigate the dynamic track-ground response subjected to train moving loads. The track dynamic responses in terms of time history track vertical displacement and ground displacement for various track-ground conditions are presented and compared the performance of geocell reinforced ballasted railway track with the unreinforced section. The outcomes of this study are explored and discussed.

1. Introduction

All over the world, the high-speed railway networks are developing speedily to fulfil the growing demand for faster transportation. The current world train speed record (603 km/h) is achieved by the Japanese bullet train (L0 series) on 21 April 2015 using the maglev technology. The faster trains apply higher repeated cyclic stresses on ballasted railway track, which may lead to undue plastic settlement as well as progressive shear failure especially when the track founded on soft subgrade. Moreover, the demand of heavier freight trains are increasing to carry the bulky products from one area to another. The high amplitude of dynamic loads (e.g., freight trains) may damage further and more rapidly the existing track due to excessive vertical and lateral track deflection that call for more recurrent maintenance. Therefore, track stabilization is often essential to improve its performance and increase longevity. Geo-synthetics are utilised as reinforcement in various structures such as embankments, steep slopes and retaining walls on soft soils. Also, geo-synthetics can also be applied as reinforcement in railway tracks. Geocells, a honeycomb like geo-synthetic act as a cellular confinement system filled with a suitable granular material, which is used in stabilizing transport infrastructure

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[1]. The performance of geocell confinement with various types of infill materials has previously been examined by several authors [2-4]. It was stated that during loading, geocells increase the stiffness of the infill materials, and enrich the load bearing capacity, and thus enhance the overall track performance [5, 6].

In the literature, several theoretical and numerical models have been established to understand the behaviour of track-ground response during a train passage. The methods implemented including analytical models [7-13], the numerical models based on finite element (FE) and boundary element (BE) method [14-20]. Several researchers [21-24] used the equivalent composite technique to model geocell reinforced soil in a two-dimensional environment. Hegde and Sitharam [25] examined the effectiveness of geocell reinforced soil in 3-dimensional condition under static loading. In addition, Leshchinsky and Ling [26] investigated the influence of geocell mattress on railway substructure under cyclic loading. However, there is a very limited number of studies that investigated the performance of geocell reinforced railway substructure under true train moving loads. It should be noted that the assumption of static or cyclic loading is highly controversial to simulate the dynamic track-ground response subjected to train moving loads [27].

In this study, a classy three-dimensional (3D) finite element (FE) model which was formerly validated by Sayeed and Shahin [28] is used to investigate the dynamic behaviour of ballasted railway track foundation. To investigate the usefulness of geocell reinforcement in the railway track, the dynamic responses of track-ground system for various track-ground parameters with and without geocell confinement are compared. The obtained results are explored and discussed.

2. Finite element modelling

In this study, the finite element based software GTS-NX [29] is used to develop the three-dimensional model of the ballasted railway track. This software is chosen because of its excellent capability of capturing the true train moving loads. In this section, the finite element modelling and simulations are described briefly.

FE model of ballasted railway track

Figure 1 presents the 3D FE model of the ballasted railway track which is used for exploring the dynamic response of the track-ground system. The track model dimensions are 15 m depth, 36 m wide and 80 m long. The rails are charac terized by one-dimensional (1D) elastic beam element whose dynamic modulus of elasticity equal to 210 GPa, Poisson's ration, ν = 0.30. A UIC-60 section (Moment of inertia = 3.04 × 10-5 m4) running along the track length is assumed for the rail, which is fixed to the sleepers by rail pads. The rail pads are modelled by elastic link element which stiffness is 100 MN/m. The sleepers are modelled using 3D solid elements, which is simulated as linear elastic (LE) materials (modulus of elasticity = 30 GPa and ν = 0.20). The sleepers' dimensions are 2.50 m long, 0.27 m wide and 0.2 m depth. The sleepers are placed along the rail at 0.6 m spacing. The ballasted railway track substructure elements (i.e. ballast, subballast and subgrade) are also modelled using 3D solid elements. The ballast and subballast are modelled using elastoplastic Mohr-Coulomb (MC) materials, whereas the subgrade is considered as linear elastic (LE) materials due to the lack of information about the plasticity characteristics and to reduce the simulation time. To characterize the geocell, a linear elastic model is used. Rhomboidal shape geocells are formed to deliver a more identi cal stress distribution which avoid meshing problems that may possibly appear because of the complicated nature of the 3D mesh configurations. The properties of all substructure materials used in the FE model are summarized in Table 1. The adopted values of the table are based on similar values given by other researchers [26, 30].

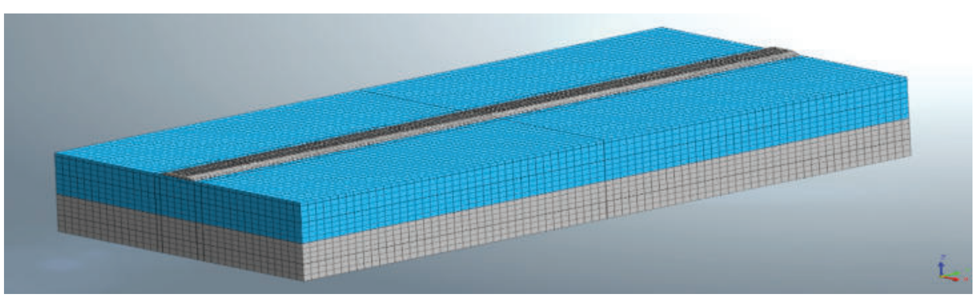

Figure 1. The 3D FE model of the railway track-ground system.

The standard geometry of ballasted railway track and the stabilized railway track with geocell confinement is shown in Figure 2. The geocell layer is located in the ballast layer at 0.25 m below the sleepers to prevent construction damage plus stress concentrations caused by the wheel loads. Figure 2b depicts the geometry of the ballasted railway embankment with a geocell layer.

Table 1. Material properties used in the FE model.

Material Properties	**Ballast**	**Subballast**	**Subgrade Soil**	**Geocell**
Dynamic modulus of elasticity, *E* (MPa)	150	150	15	2000
Poissons ratio, *v*	0.30	0.30	0.35	0.35
Unit weight, γ (kN/m^3)	18.0	21.0	16.8	15.1
Cohesion, *c* (kPa)	0.00	0.00	---	---
Friction Angle, ϕ^o	45.0	40.0	---	---
Thickness, *H* (m)	0.30	0.15	15.0	0.15
Damping Ratio, ξ	0.03	0.03	0.03	0.03

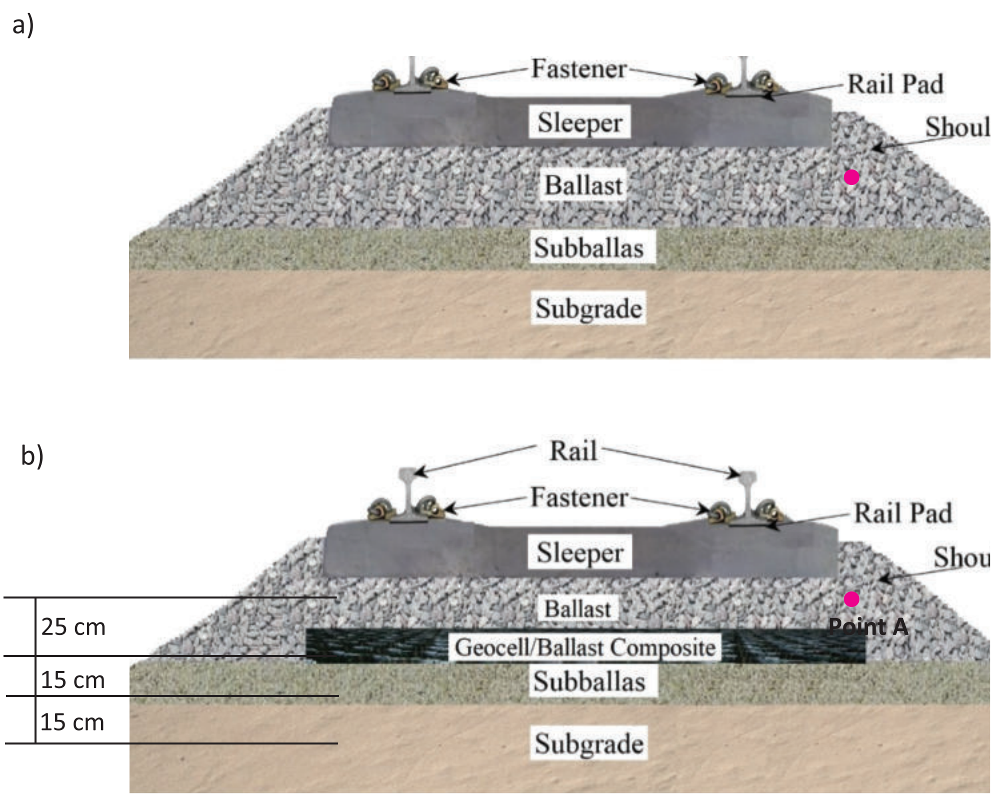

Figure 2. Railway geometry: a) with absence of geocell, b) with geocell confinement.

In the dynamic analyses, the size of finite element, time step and model boundaries have to be chosen accurately to confirm the precision of the outcomes [19]. Generally, the element dimension of the finite element numerical model should be calculated based on the lowest wavelength which permits to simulate the high-frequency wave appropriately. Consequently, the dimensions of the 3D FE model constituents are chosen in this study. In the FE model, viscous dampers are linked to vertical boundaries to absorb the incident *p*-waves and *s*-waves, and thus characterize infinite boundary conditions as recommended by several scholars [31, 32]. To simulate hard rock condition at the track bed, all nodes at the lowermost boundary are set to be fixed in all direction. The material damping of the FE model is characterized by Rayleigh damping that is usually utilised for dynamic analyses.

Simulations of train moving loads (X-2000 HST)

In this study, the X-2000 passenger train loading is simulated to investigate the track-ground response. Figure 3 shows the geometry, and Table 2 summarizes the standard geometry and wheel loads of the X-2000 HST.

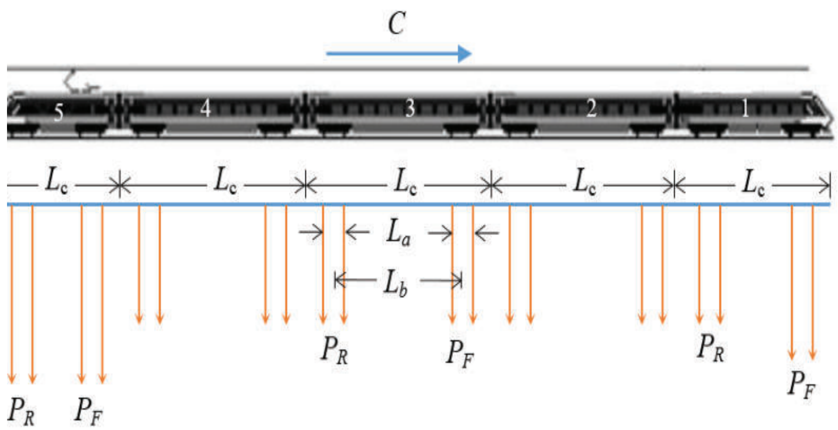

Figure 3. Geometry of the X-2000 HST [33]

Table 2. Geometry and wheel loads of the X-2000 HST[33]

Car number, *n*	**Spacing**			**Standard wheel load**	
	Car length, L_c (m)	Bogie to bogie distance, L_b (m)	Axle to axle distance, L_a (m)	Front wheel load, P_F	Rear wheel load, P_R
1	22.2	14.5	2.9	81.0	61.3
2	24.4	17.7	2.9	61.3	61.3
3	24.4	17.7	2.9	61.3	61.3
4	24.4	17.7	2.9	61.3	61.3
5	17.2	9.5	2.9	90.0	90.0

In the FE modelling, the train moving loads are simulated in according to the method proposed by Araújo [34]. In this simulation, the finite element rail nodes (denoted as *loading nodes*), which are tightly linked to the sleepers, are connected to a wheel load whose value varies over time. The moving loads is considered as triangular pulses delivered among three consecutive loading nodes (Figure 4). As soon as the wheel load, *F*, leaves the previous *loading node N*, the loading amplitude at the specific node *N*+1 raises, and reaches the highest value when the wheel load is just on the loading node *N*+1, then lastly becoming zero when the wheel load arrives at the following node *N*+2. Thus, the triangular pulse shifts to the following node by a time period which is equivalent to the gap of the loading nodes divided by the speed of moving load, *C*. For instance, when the speed of train is 30 m/s (108 km/h), and the gap between any two *loading nodes* is 0.6 m, then the wheel load will move the space between two successive *loading nodes* in 0.02 sec. Similarly, a series of wheel loads of the X-2000 HST will be moving at a train speed 30 m/s along the railway track. It should be noted that the developed FE model of the ballasted railway track is 80 m long, which enables to capture the track response for at least 3 cars of the X-2000 HST at a single instant. For example, when the front wheel of the first car leaves the track, the front wheel of the 4th car enters the track. In this study, to reproduce the transient phenomenon of wave propagation, all the FE analyses are executed in the time domain manner, which is more natural as suggested by Kouroussis, et al. [35].

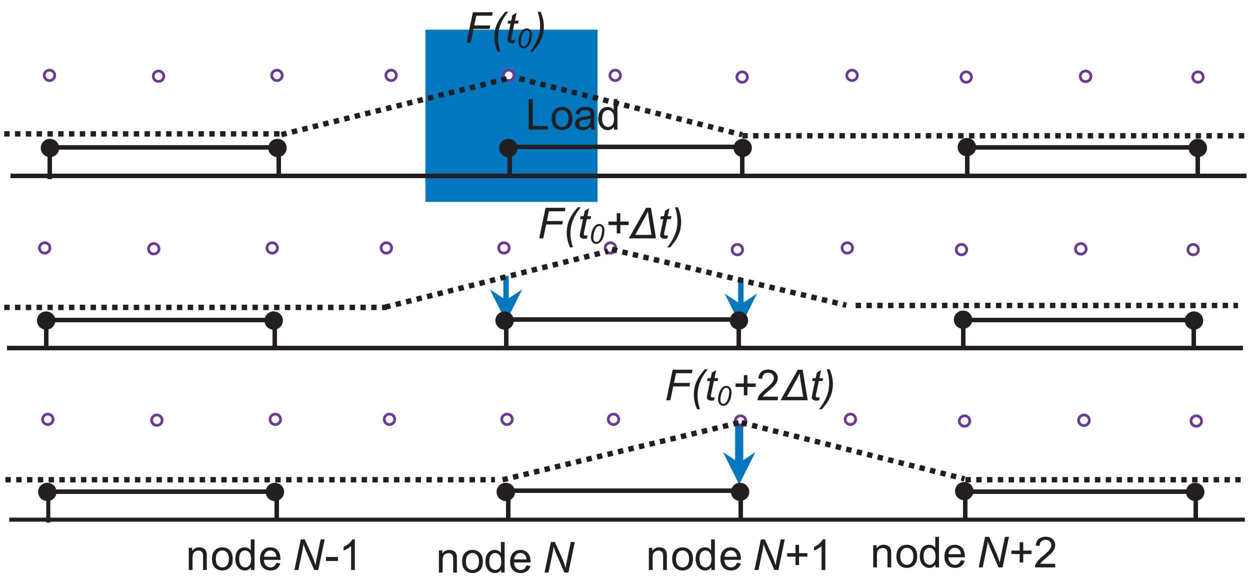

Figure 4. Simulation of moving loads [34].

3. Parametric study

In this section, to evaluate the effect of geocell reinforcement on track-ground response, a series of simulations are executed on the ballasted railway track under train moving loads. As stated earlier, the X-2000 HST is considered as the train moving loads. The speed of the train moving loads is reflected as 108 km/hr (30 m/s). It should be noted that in all the FE analyses, the materials properties given in Table 1 is considered remain unchanged unless otherwise indicated.

Stiffness of geocell

Geocell is made with a diversity of polymeric constituents. Consequently, there is a large range of Young's modulus for different geocells made of different polymers. Therefore, this section focuses on the effect of geocell stiffness on vertical track displacement. To address this matter, finite element analyses are executed on the ballasted stabilized railway track with different geocell stiffness. The stiffness of the geocells is varied from very low elastic modulus of rubber (E = 0.1 GPa) to very high elastic modulus like that of steel (E = 200 GPa) and in between 2 GPa is considered as the nominal value.

Figure 5 shows the time history vertical track displacement at point A (see Figure 2, i.e., just below the sleeper end) for various geocell stiffness. In general, the geocell confinement reduces the track deflection. About 12% and 19% reductions in track deflection can be achieved by geocell confinement while the Young's modulus of geocells are 2 GPa and 200 GPa, respectively. However, the reduction in vertical track deflection is insignificant while the geocell stiffness is very low (E = 0.1 GPa). The obtained outcomes of this study show good consistency with the behaviour published in [36-37].

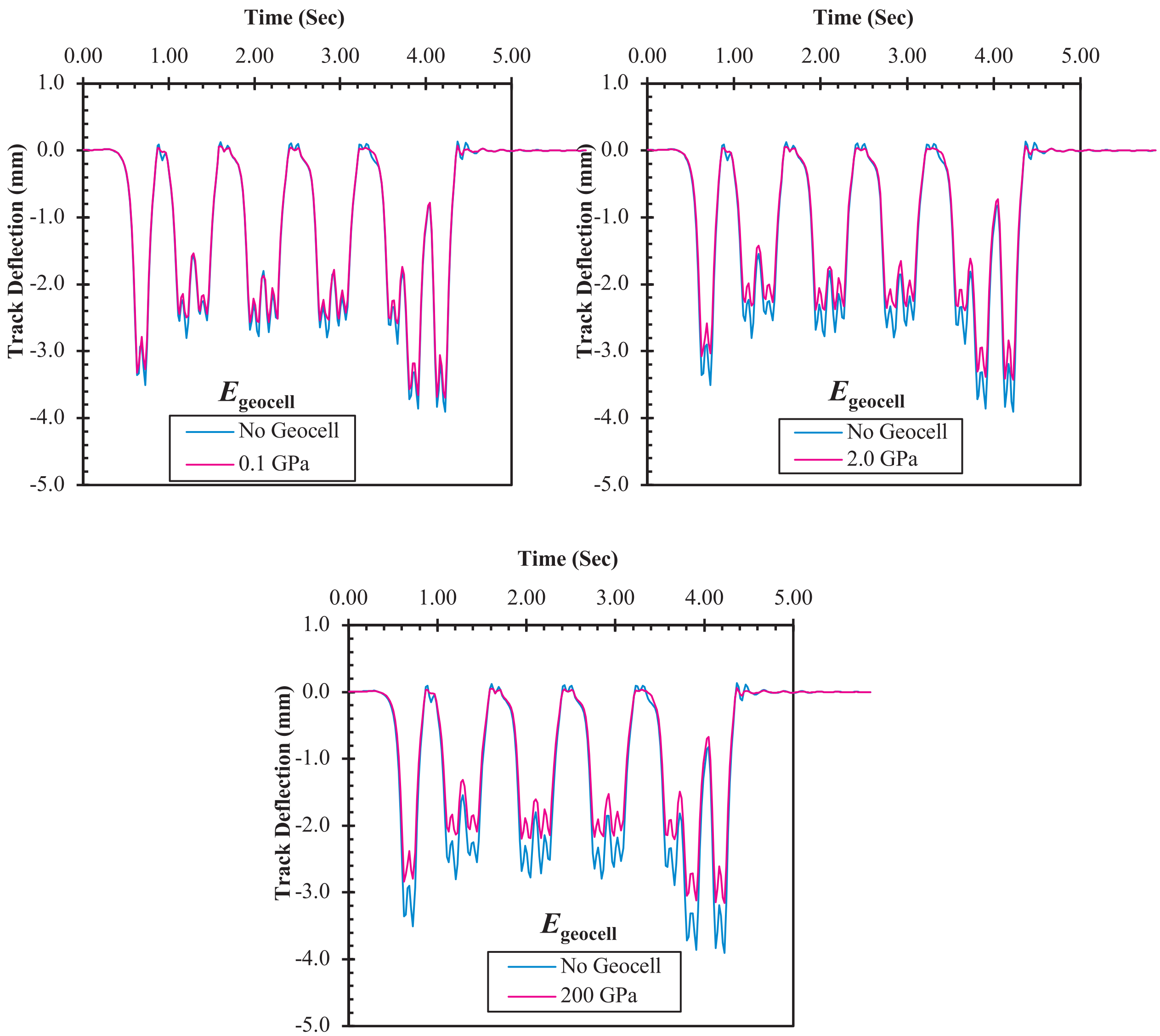

Figure 5. Time history vertical track displacement with no geocell and with geocell confinement for different geocell stiffness.

Stiffness of ballast

In a conventional ballasted railway track, various types of ballast, explicitly dolomite, basalt, quartzite and granite are used, whose stiffness property differ from very low to high. Therefore, the influence of various ballast stiffness with and without geocell confinement on the vertical track displacement response is investigated in this section. To examine the effect of ballast stiffness, three different modulus of elasticity values for ballast (E_b = 75, 150 and 450 MPa) are used, and the other track materials properties including geocell are kept remain the same as given in Table 1.

Figure 6 presents the time history vertical track displacement for various ballast stiffness. It can be seen that track deflection decreases with the increase of ballast stiffness. In addition, the geocell confinement reduces the track deflection in all cases. However, the reduction in vertical track deflection by geocell confinement in soft ballast is about 23% (Figure 6a), whereas the reduction is only 8% in stiff ballast (Figure 6c). These results indicate that geocell confinement can improve the track performance significantly, where the stiffness of ballast is very low. These results show good consistency with the results reported by Leshchinsky and Ling [26].

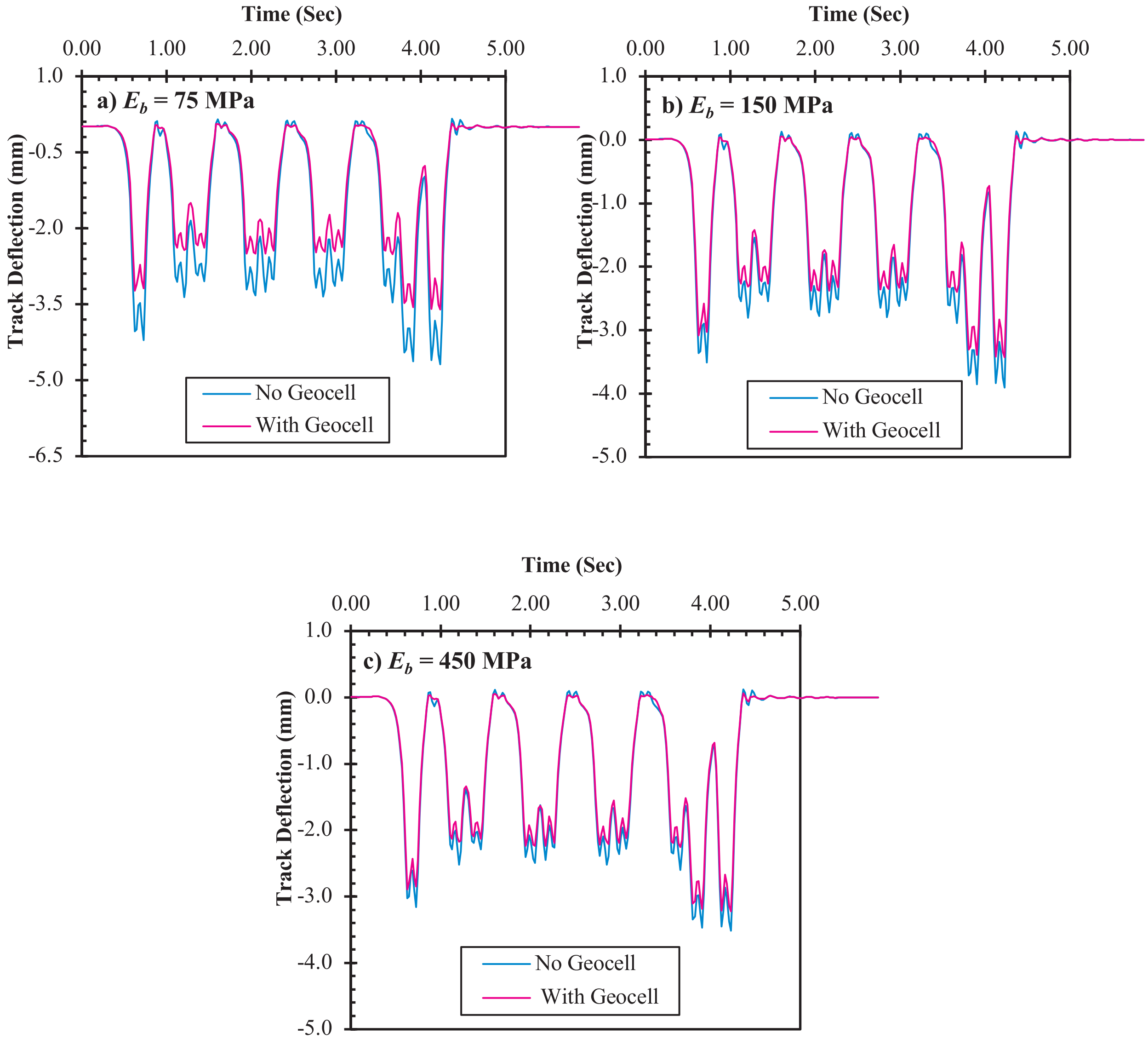

Figure 6. Time history vertical track displacement with no geocell and with geocell confinement for different ballast modulus.

Stiffness of subgrade

The wave propagation velocity in any soil medium is substantially reliant on its stiffness, thus it is important to investigate how the geocell confinement can improve the track-ground response for different subgrade stiffness. To investigate this effect, three different values of subgrade modulus are considered (E_s = 5, 15, and 120 MPa). The impact of track subgrade stiffness together with the absence of geocell or with geocell confinement is presented in Figure 7, in terms of the time history track vertical deflection. In general, the track vertical deflection increases with the decreases of subgrade stiffness. In addition, geocell confinement reduces the track vertical deflection although it is insignificant as anticipated. The percentage reduction in sleeper deflection is less prominent especially when the railway track founded on very soft subgrade. The greatest percentage reduction in track vertical displacement happened while the ballast embankment founded on a very stiff subgrade. The obtained outcomes are reliable with the results reported by Biabani, et al. [36].

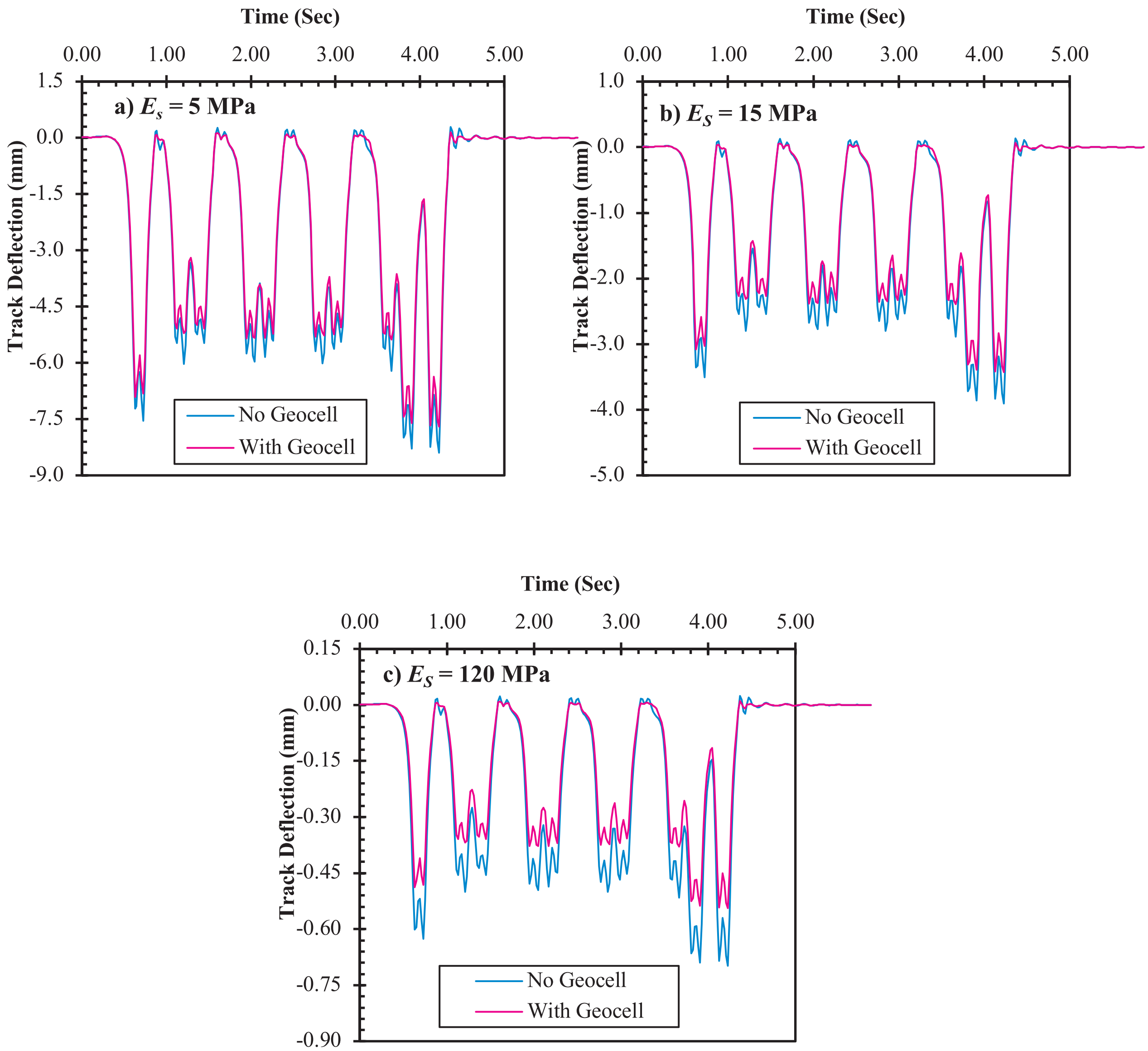

Figure 7. Time history vertical track displacement with no geocell and with geocell confinement for different subgrade modulus.

Train speeds

As train speed plays a significant role in the track-ground system, the effect of different train speeds, including the subcritical speed, critical speed and supercritical speed, on a track-ground system with or without geocell confinement is investigated. Critical speed is the train speed at which the railway track and surrounding soil are extremely intensified and huge vibrations occur. The train speed smaller than the critical speed is called the subcritical speed and the speed higher than the critical speed is called as supercritical speed. The sleeper maximum downward deflections for each train speed are plotted in Figure 8. It is noted that with the increase of train speed, the sleeper maximum deflection normally increases. At the critical speed, sleeper deflection reaches the highest value, and then it reduces with further raise of the train speed in both the track condition with or without geocell confinement. It is noted that geocell confinement does not have effect on the critical speed of the track-ground system. However, the geocell confinement reduces the track vertical displacement in all speeds. These behaviours present good uniformity with the results reported by Sun, et al. [38].

Figure 9 presents the track vibrations in terms of the vertical displacements of ground surface from the track centre to the neighbouring ground at critical speed for the ballasted track without geocell confinement and with geocell confinement. It can be seen that the highest amplitude of ground vibrations occurs at the unstabilized ballasted railway track centre compared to the stabilized track condition (with geocell confinement). It can also be seen that, for any track condition, the ground vertical displacement decreases with the remoteness from the track centre, as expected. In addition, it can be noted that without geocell confinement, the area included 14 m away from the track centre in both sides vibrates in a significant level at the critical train speed which could be harmful for operation of trains and may also be a possible source of failure for the neighbouring structures. However, the zone of vibration can be reduced to within 6 m away from the track centre with geocell confinement for the specified track-ground properties given in Table 1.

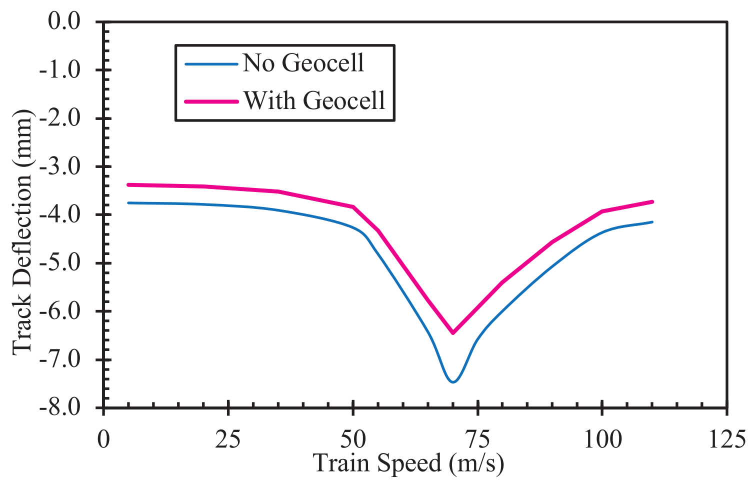

Figure 8. The sleeper maximum downward deflections versus the train speeds.

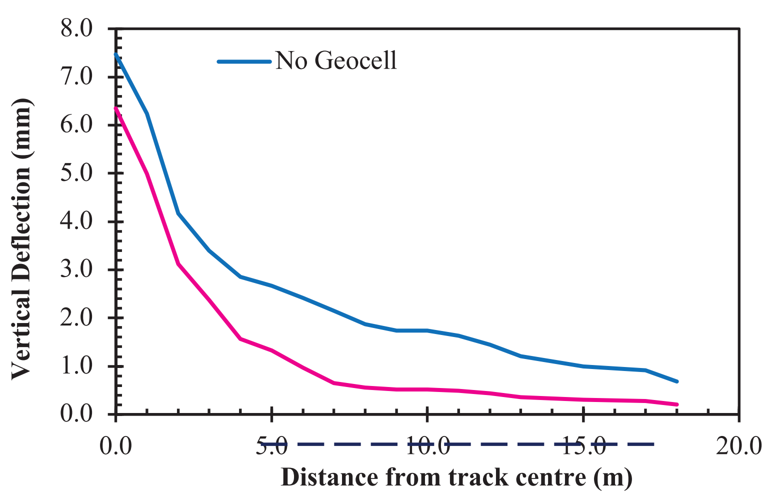

Figure 9. Variation of ground displacement from the track centre at critical train speeds.

4. Summary and conclusions

In this paper, dynamic behaviours of geocell reinforced ballasted railway track subjected to train moving loads are investigated using a classy three-dimensional finite elements modelling. A parametric study is performed by varying stiffness of geocell, ballast modulus, subgrade modulus and train speed. By comparing the track performance of the ballasted railway track with and without geocell confinement, the importance of geocell is investigated. The conclusions drawn from this study are as follows:

- Due to the geocell confinement, the stiffness of ballasted embankment increases, and consequently it reduces the track deflection.
- The track deflection decreases with the increase of geocell stiffness.
- The geocell confinement can improve the track performance significantly, especially where the stiffness of ballast is very low. However, the geocell confinement cannot significantly improve the performance of the ballasted railway track while it is founded on soft subgrade.
- Geocell reinforcement does not have effect on critical speed of a railway track-ground system, although it reduces the track deflection in each speed.
- Geocell reinforcement in the ballasted layer can reduce the vibration in the track as well as in the nearby structures.

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