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INFLUENCE OF THE NUMBER OF TRAIN CARRIAGES ON TRAIN-INDUCED GROUND VIBRATIONS

*Pham Ngoc Thach[1]

[1] Institute of Civil Engineering, Hochiminh City University of Transport, Vietnam

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ABSTRACT: Trainload is characterized by a number of factors such as axle load magnitude, number of carriages, train speed, etc. These factors likely contribute to the ground vibration induced by a high-speed train. While vibration effects associated with train speed have received much research attention in the literature, limited attention has been paid to the effects associated with the number of train carriages. In this study, we investigate how the number of train carriages affects ground vibrations caused by a high-speed train. A finite element model is used to simulate the vibration of a layered ground caused by a Shinkansen train moving at a speed of 70 m/s (252 km/h). There are 8 cases of trainload considered, and each case corresponds to a number of train carriages. The simulation result shows that the number of train carriages has a significant influence on the amplitude of ground vibration. The influence is more pronounced for locations near the excitation source. When the train has 4 or fewer carriages, the vibration amplitude increases with increasing the number of train carriages. However, when the train has 4 or more carriages, the vibration amplitude remains unchanged. It is therefore recommended that in a simulation of train-induced ground vibration, we should only use a sufficient number of train carriages (about 4 to 5 carriages). If more train carriages are used, we still get the same result, but the computational cost increases significantly.

Keywords: Ground vibration, Finite element simulation, Trainload, Number of carriages

1. INTRODUCTION

Railway transportation represents a convenient and environmentally friendly alternative to road and air transportation. The last decades have been marked by the rapid development of high-speed railway systems in many countries throughout the world. Like many other means of transportation, high-speed trains are not free of environmental problems. When trains run at high speeds, they generate ground vibrations. Problems relating to train-induced ground vibrations are now an engineering challenge in densely populated urban areas due to the increase demand of higher speeds and heavier loads [1-5]. Although ground vibrations induced by high-speed trains may not result in the collapse of buildings as earthquakes do, they can be strong enough to affect passenger safety, maintenance costs, and passenger comfort. In addition, when these ground vibrations propagate outward from the track, they interact with the surrounding environment and can cause negative side effects in urbanized areas, for example, they annoy people living alongside the railway, or they cause delicate instruments located inside buildings to malfunction [1,6-10].

Ground response to a moving load depends largely on the relation between the moving speed and the characteristic wave speeds of the ground. In elastodynamics theory, it has been expected to categorize moving load problems as sub-seismic, super seismic, and Tran seismic, depending on whether the moving speed is less than V_R, greater than V_P, or intermediate between these speeds (where V_R and V_P are the Rayleigh and compressive wave speed of the ground). Analytical studies have shown that within the sub-seismic range, the ground response to a moving load is essentially quasi-static; that is, the displacement and stress fields are essentially static and simply move with the load. In contrast to the sub-seismic case, both the Tran seismic and super seismic cases are characterized by large dynamic effects in the ground response [1,6,11]. Based on the above fundamental knowledge, complex behaviors of ground vibrations due to high-speed trains have been subsequently studied by many researchers. They all emphasized that as the train speed increases, the intensity of railway-generated vibrations generally becomes larger. Especially when the train speed approaches critical speeds, which are determined by the natural vibration properties of the system, the ground vibration is particularly high as a consequence of a “resonance-like“ phenomenon [3,6,11,12].

It is noted from the studies cited above that they all assumed a particular trainload pattern with a fixed number of train carriages and focused on the effects of train speed on ground vibration. As a consequence, less attention has been paid to the effects associated with the number of train carriages. Specifically, each train has a number of carriages, and each carriage has wheel axles and weight (self-weight and passengers). The weight is distributed to the axles to form axle forces. All of the axle forces form a trainload. If the number of carriages increases, the trainload contains more axle forces, and the time taken for the trainload to act on a computation model will increase. This implies that increasing the number of carriages may significantly affect the train-induced ground vibration. Therefore, in this study, we investigate how the number of train carriages affects ground vibrations caused by a high-speed train.

In this paper, a simulation method is first presented. The method is then used to simulate the vibration of a layered ground caused by a Shinkansen train moving at a high speed. Simulation results are presented and discussed to provide a recommendation on the number of train carriages that should be used in a simulation.

2. RESEARCH SIGNIFICANCE

Trainload is characterized by a number of factors, such as axle load magnitude, number of carriages, train speed, etc. These factors likely contribute to the ground vibration induced by a high-speed train. While vibration effects associated with train speed have received much research attention in the literature, limited attention has been paid to the effects associated with the number of train carriages. Therefore, in this study, we investigate how the number of train carriages affects ground vibrations caused by a high-speed train. The significance of this study is to gain more understanding of how the number of train carriages affects train-induced ground vibration and to provide a recommendation on how many train carriages should be used in a simulation so that computational efficiency can be achieved.

3. SIMULATION METHOD

Trainload is modeled by first assuming that rail-wheel contact is perfect and that the wheel loads act on the rails as constant-magnitude moving forces. These moving forces are then transferred to the ballast surface as a series of equivalent concentrated forces by using the method developed in [13]. The finite element method is then used to analyze the ballast-embankment-ground system subjected to the equivalent forces. The complex geometry of ballast, embankment and soil layers is represented by 8-node hexahedral finite elements with reduced integration and hourglass control [14]. To minimize the influence of wave reflection on observation locations of interest, infinite elements are used on the boundaries of the finite element model [15]. The materials are assumed to behave elastically with three material parameters: shear wave speed, Rayleigh wave speed, and mass density [16]. A lumped mass scheme is used to discretely represent the continuous distribution of mass within each finite element [17]. Rayleigh damping is used to represent energy-dissipating mechanisms in the simulation model [17]. The explicit central difference method is used for time integration of the dynamic equilibrium equations [14]. Note that equations involved in the representation of trainload can be found in [13]; the program ABAQUS [18] is used for finite element simulation, in which both the infinite element and explicit solver are integrated.

To verify the simulation method, we consider the problem: a unit axle load moving on a track resting on an elastic half-space. The moving speed is 60 m/s. The density, Rayleigh, and shear wave speeds of the half-space are 1800 kg/m^3, 60.3 m/s, and 65 m/s, respectively. The problem is solved by the FEM-based method and an analytical method. The FEM model of the considered problem is shown in Fig. 1a, and Fig. 1b is a cross-sectional slice of the model. The analytical method was developed by Krylov [13]. By using Green's function formalism, Krylov proposed a frequency-domain analytical solution to train-induced ground vibration velocity for the case of a track resting on an elastic half-space. Fig. 2 shows the Fourier amplitude spectrum of vertical velocity at the observation point (see Fig. 1) resulting from both methods. It can be observed from the figure that the FEM solution well represents the velocity amplitude at all important frequencies.

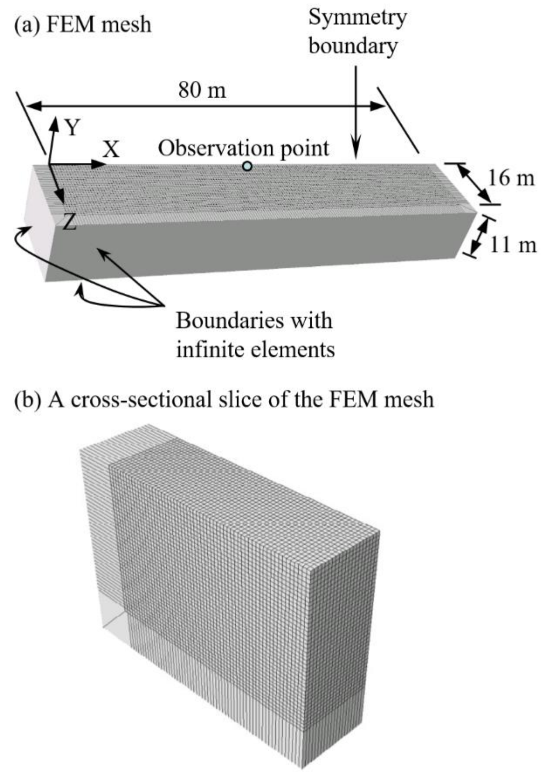

Fig. 1 Finite-element mesh of half-space

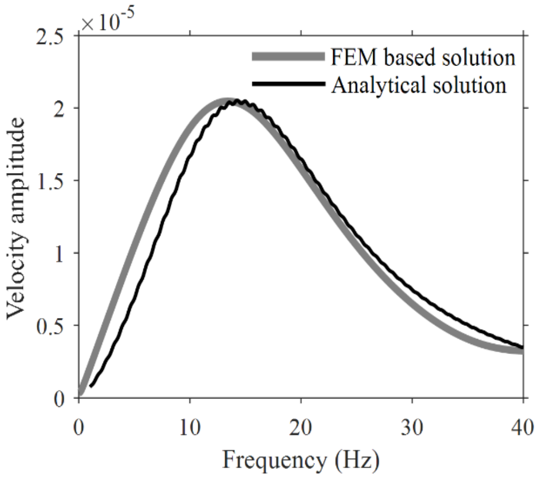

Fig. 2 Amplitude spectrum of vertical velocity

4. INFLUENCE OF THE NUMBER OF CARRIAGES ON GROUND VIBRATION

The presented simulation method is used to simulate the vibration of a layered ground caused by a Shinkansen train moving at a speed of 70 m/s. There are 8 cases of trainload, and each case corresponds to a number of train carriages. The axle load pattern in train carriages is shown in Fig. 3. Ground profile is shown in Fig. 4 and material parameters are given in Table 1, in which V_S is characteristic shear wave speed, V_R is characteristic Rayleigh wave speed and ρ is density.

Table 1 Material parameters

Material	Thickness (m)	V_S (m/s)	V_R (m/s)	ρ (kg/m^3)
Ballast	1.2	210	194.8	2000
Sand 1	0.9	63	58.5	1900
Clay 1	8.0	60	55.7	1800
Clay 2	6.0	87	80.7	1800
Sand 2	30	98	90.9	1850

Fig. 5 shows the finite element model. The model is meshed using 8-node hexahedral elements with reduced integration and hourglass control [14]. The fixed boundary is used at the bottom to represent the bedrock. On the remaining boundaries, infinite elements are used to represent the infinite boundary condition [15]. The model has a total of 2296350 finite elements and 46656 infinite elements. A lumped mass scheme is used to represent the mass within each finite element [14]. Rayleigh damping is used to represent energy dissipating mechanisms [17], in which the mass and stiffness proportional damping constants are selected to provide slight damping ratios of 3÷6% in the frequency range of 3÷40 Hz, as shown in Fig. 6.

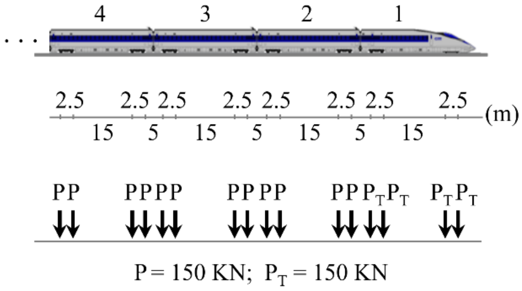

Fig. 3 Axle load pattern in train carriages

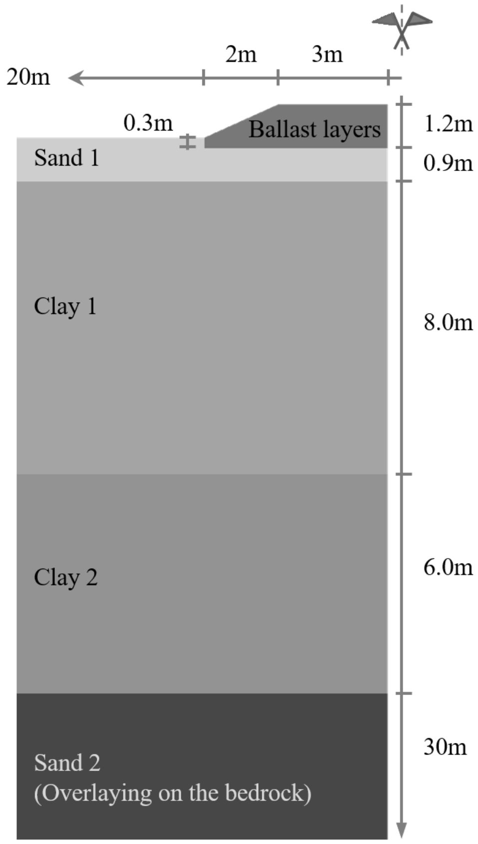

Fig. 4 Ground profile

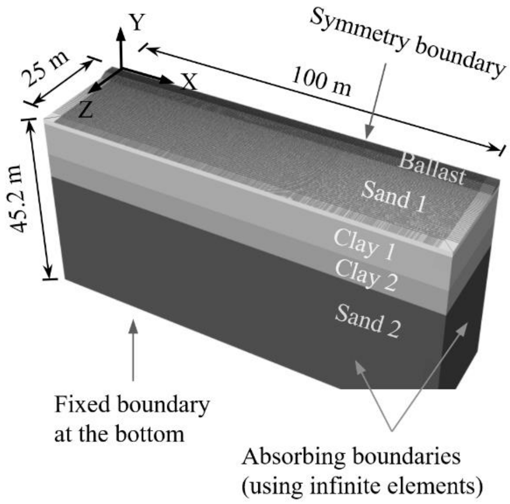

Fig. 5 3D finite element model

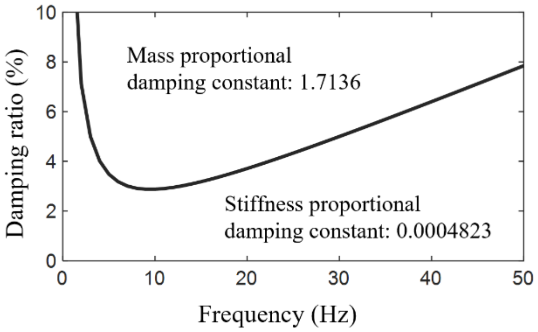

Fig. 6 Rayleigh damping

Fig. 7 shows the surface displacement field at a time instant (magnified 1000 times). It can be observed from the figure that each axle force generates a radiated wavefront whose apex is at the force, and the wave field generated by the train is the superposition of the fields generated by each axle force.

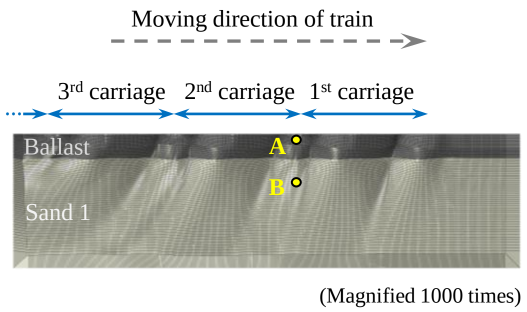

Fig. 7 Plan-view of surface displacement field.

Let us focus on points A and B in Fig. 7. Point A represents a location on the ballast surface, and point B represents a location outside the ballast surface, which is 9 m far from the ballast center. When the train passes these points, their vertical displacement and velocity time histories are recorded and presented in Fig. 8, Fig. 9, Fig. 10, and Fig. 11 for the eight considered cases. It can be observed from the figures that, at point A, the cases have a similar displacement and velocity pattern under each carriage but have different displacement and velocity amplitude. At point B, the response is smaller than at point A, and the cases also have a similar displacement and velocity pattern under each carriage but have different displacement and velocity amplitude.

To gain more understanding, the maximum displacement at point A for each case in Fig. 8 is plotted versus the number of train carriages as shown in Fig. 12. It can be observed from the figure that the number of train carriages has a significant influence on the amplitude of ground vibration.

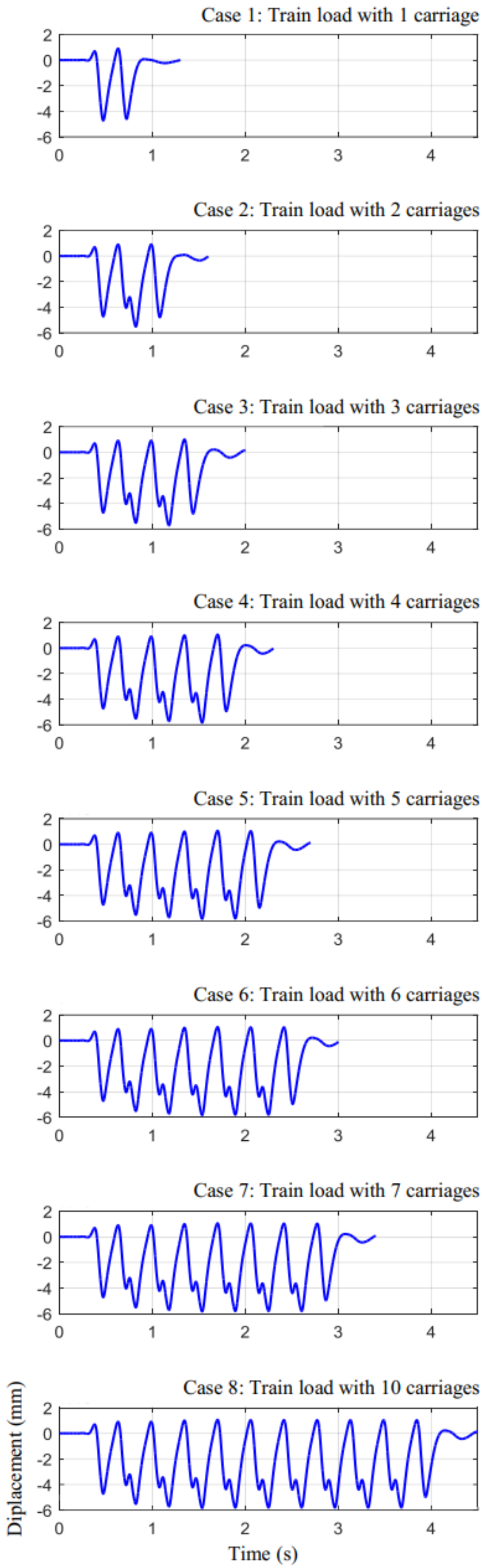

Fig. 8 Displacement time history at point A

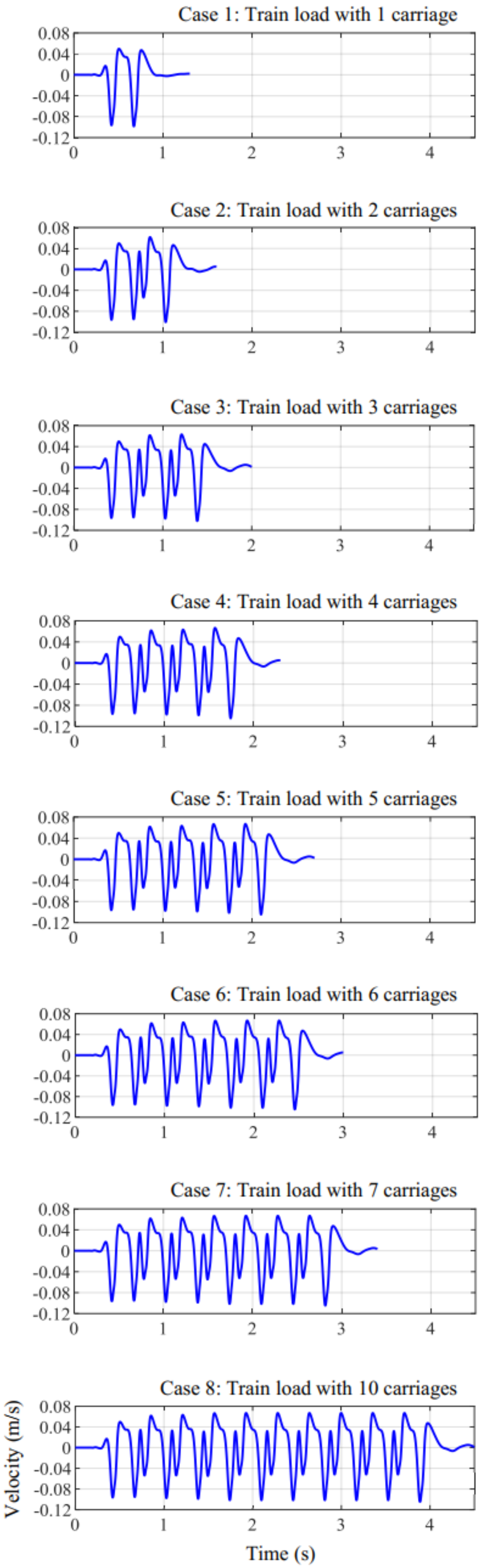

Fig. 9 Velocity time history at point A

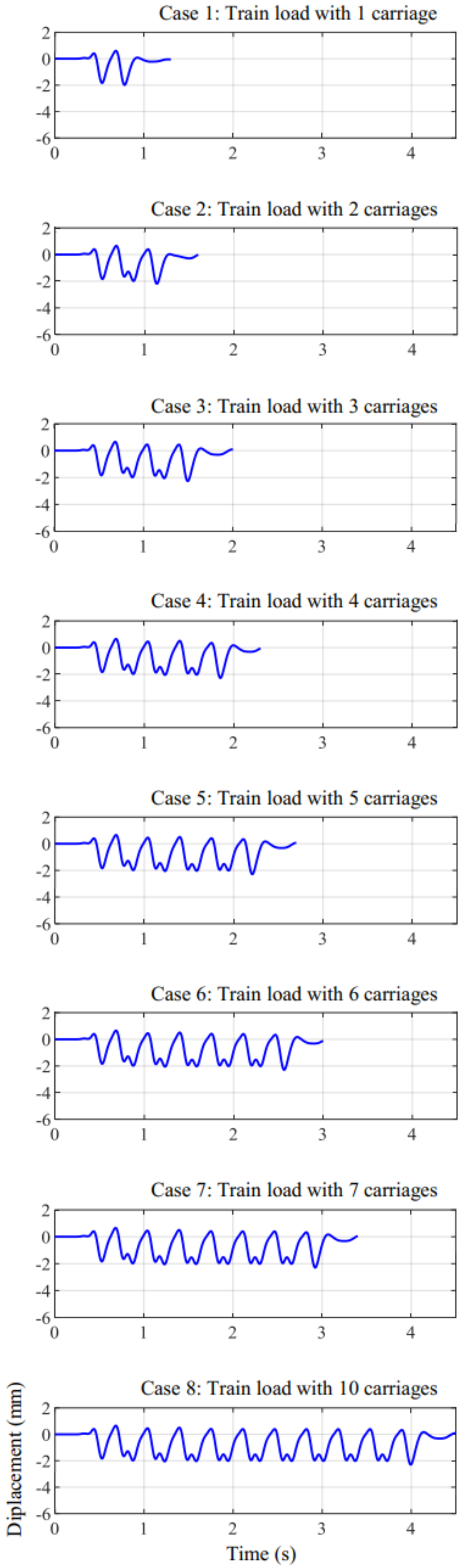

Fig. 10 Displacement time history at point B

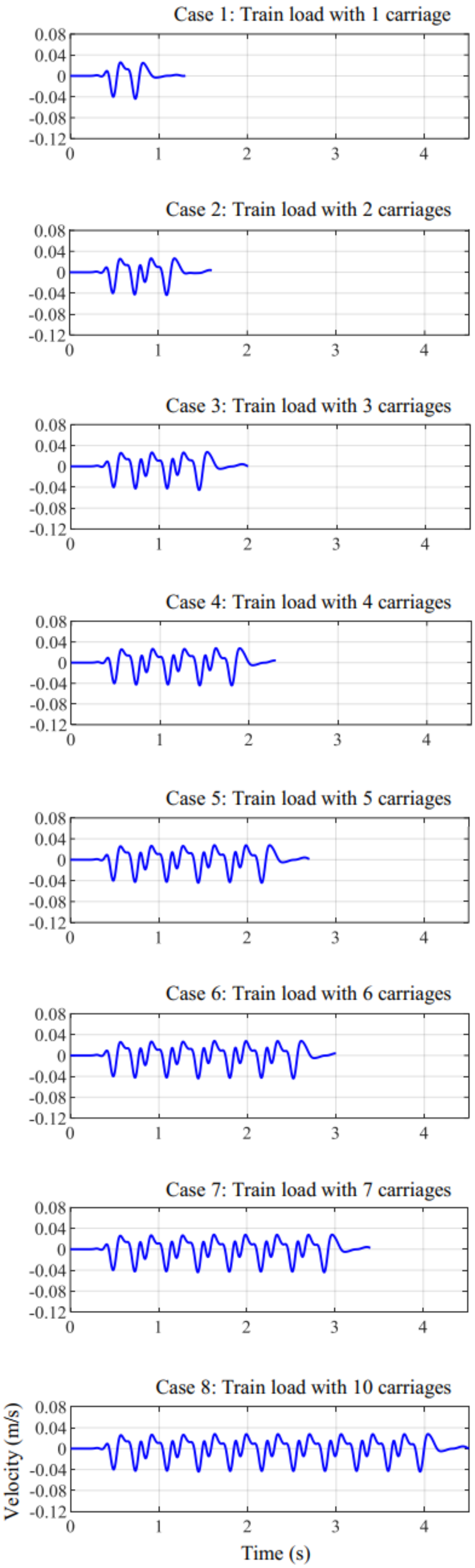

Fig. 11 Velocity time history at point B

In particular, the displacement amplitude in the case of 1, 2, 3 and 4 train carriages is 4.72 mm, 5.51 mm, 5.71 mm and 5.82 mm, respectively. When the train has 4 or more carriages, the displacement amplitude remains at a value of 5.82 mm.

The maximum velocity at point A for each case in Fig. 9 is plotted versus the number of train carriages as shown in Fig. 13. It can be observed that the velocity amplitude in the case of 1, 2, 3 and 4 train carriages is 0.0985 m/s, 0.1008 m/s, 0.1030 m/s and 0.1047 ms/, respectively. When the train has 4 or more carriages, the velocity amplitude remains at a value of 0.1047 m/s.

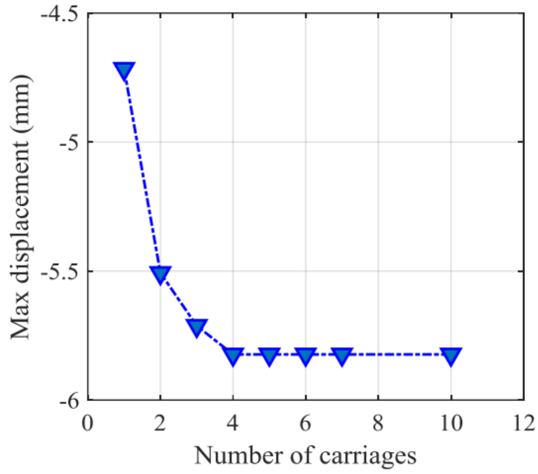

Fig. 12 Max displacement at point A

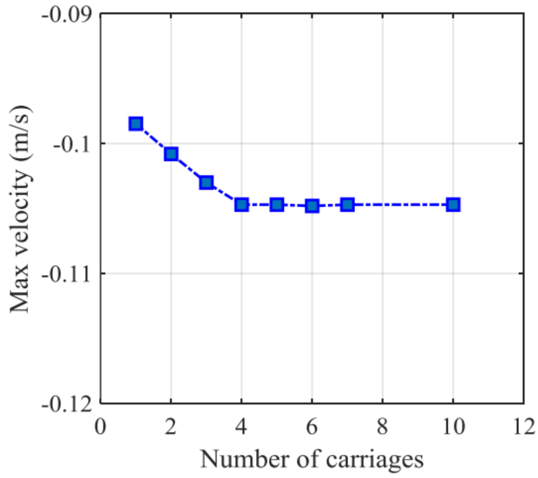

Fig. 13 Max velocity at point A

For point B, which is outside of the ballast, the maximum displacement for each case in Fig. 10 is plotted versus the number of train carriages, as shown in Fig. 14. It can be observed from the figure that the displacement amplitude in the case of 1, 2 and 3 train carriages is 1.98 mm, 2.19 mm and 2.27 mm, respectively. When the train has 3 or more carriages, the displacement amplitude remains at a value of 2.27 mm. The maximum velocity at point B for each case in Fig. 11 is plotted versus the number of train carriages as shown in Fig. 15. It can be observed that the velocity amplitude is less influenced by the number of train carriages and remains at a value of about 0.044 m/s.

The above observations indicate that the number of train carriages has a significant influence on the amplitude of ground vibration. The influence is more pronounced for locations inside the ballast, namely near the excitation source. The observations also imply that in a simulation of train-induced ground vibrations, using about 4 or 5 train carriages should be enough to represent critical simulation cases. If more train carriages are used, we still get the same result, but it takes a longer time duration for the train to pass through the model (as can be seen in figures 8 to 11), thus increasing simulation time and computational cost.

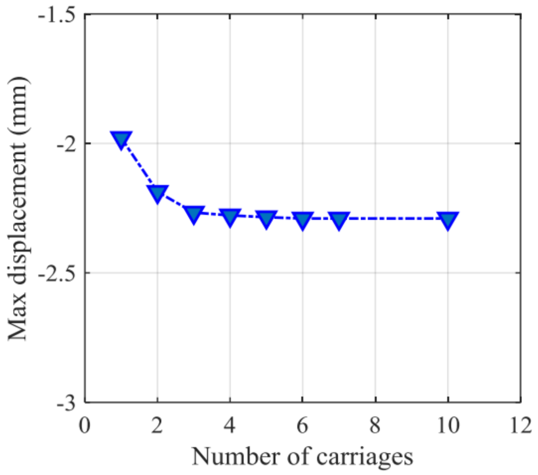

Fig. 14 Max displacement at point B

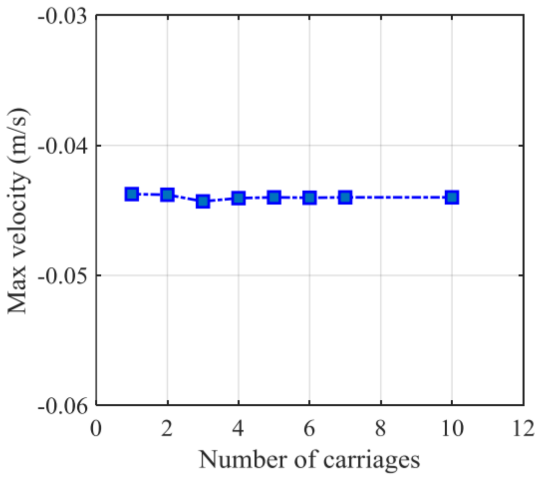

Fig. 15 Max velocity at point B

5. CONCLUSION

The number of train carriages has a significant influence on the amplitude of ground vibration. The influence is more pronounced for locations inside the ballast, namely near the excitation source.

When the train has 4 or fewer carriages, the vibration amplitude increases with increasing the number of train carriages. However, when the train has 4 or more carriages, the vibration amplitude remains unchanged. It is therefore recommended that in a simulation of train-induced ground vibration, we should only use a sufficient number of train carriages (about 4 to 5 carriages). If more train carriages are used, we still get the same result, but the computational cost increases significantly.

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