INTERNATIONAL CONFERENCE ON NOISE AND VIBRATION ENGINEERING
7-9 September 2020, Leuven, Belgium

Experimental and numerical study on free field motion due to passage of high-speed train considering different types of soil

A. A. Faizan [1], O. Kırtel [1], E. Çelebi [2], A. C. Zülfikar [3], F. Göktepe [4]
[1] Sakarya University of Applied Sciences, Department of Civil Engineering
54187 Esentepe Campus, Sakarya, Turkey
e-mail: **ahad.faizan@ogr.sakarya.edu.tr**

[2] Sakarya University, Department of Civil Engineering
54187 Esentepe Campus, Sakarya, Turkey

[3] Gebze Technical University, Department of Civil Engineering
41400 Cayirova Campus, Kocaeli, Turkey

[4] Bartin University, Department of Civil Engineering
74100 Bartin/Turkey

Abstract

A field measurement of ground vibration was performed on the Istanbul-Ankara high speed railway in Sakarya-Turkey, using seismometers. By placing the seismometers at difference distances from the track, the passage of different trains were recorded. In the first part of the paper, a two-dimensional numerical model which is based on finite element method applied for the purpose of studying ground vibrations and validating experimental results. The dynamic analysis of the proposed railway-soil coupled model has been performed in the time domain under plain-strain condition by using PLAXIS 2D commercial FEM software. In the verification process, the experimental results were compared with those from numerical analysis. In the second part of the paper, the train induced vibrations for different types of soil are analysed. Analysis was performed for four types of soil; the soils were specified as soft, medium, dense and rock. High-speed train was used as a dynamic source to observe the differences in behavior of dynamic ground motions at different types of soil. Results showed that the peak acceleration values of the train induced vibrations at the soft, medium and dense sites increased dramatically compared to the rock site.

1 Introduction

With the rapid increase and development of high-speed trains, the problems such as train-induced vibration and its dynamic effects on nearby structures have become a major environmental concern in urban areas. Ground-born vibrations produced by high-speed trains posing a great challenge for field engineers to build structures in such area that are applicable for residents. The effect of vibrations generated by traffic systems on urban life and working environment has been brought to public attention since vibration has been listed as one of the seven major environmental hazards in the world [1]. Therefore, a thorough analysis of these effects is necessary to avoid possible problems for nearby buildings which may be affected by train-induced vibrations.

Recently, a considerable amount of research works into train-induced vibrations have been done. These studies can be categorized as field measuring, experimental tests, and numerical works.

Triepaischajonsak and Thompson [2] studied the train-induced ground vibration using a hybrid approach considering the train-track interaction. Yang et al. [3] developed a model to study the wave propagation in layered soils induced considering different train speeds. Lombaert and Degrande [4] investigated the excitations of train-induced ground vibration to quasi-static and dynamic and suggested a numerical model. Gupta et al. [5] studied Beijing's subway line 4 train vibrations by using combined FEM/BEM method.

In addition to the above-mentioned analytical and numerical methods, numerous experimental research studies have been performed to evaluate the train-induced ground vibration. Xia et al. [6] performed a series of in-situ experiments to study the effects of train-induced vibrations on the ground and nearby structures. Zhang and Feng [7] studied the characteristics of high-speed train induced ground vibrations in the Hu-Ning Railway by using experimental method. Degrande and Schillemans [8] measured the train-induced ground vibration near Brussels-Paris high-speed railway line with variable train speeds between 223 and 314 km/h to validate a numerical model. Çelebi et al. [9] performed a series of in-situ experiments to study the effects of open or in-filled trench barriers as a reduction measure for soil vibrations due to a moving load which is considered as stationary wave source. Auersch [10] carried out a series of measurements of ground vibration during the test runs of the ICE train with varied speed near Würzburg.

This paper mainly focuses on three aspects. Firstly, the in-situ measurement and ground-borne vibration experiment carried out by the authors on Istanbul-Ankara high-speed railway. The test train speed was 250 km/h. Secondly, a two-dimensional numerical model which is based on finite element method applied for the purpose of studying ground-borne vibrations and validating experimental results. According to the obtained results, its concluded that the simulated numerical model is capable of the replicating the experiment data and can be applied in the analysis of vibrations. Lastly, the verified model was used to study the influence of train induced vibrations for different soil conditions. Analysis was performed for four types of soil (soft, medium, dense and rock). The computational results are discussed in order to figure out some useful conclusions.

2 The characteristics of the train and test site

In July 2018, a free filed measurement on the Istanbul-Ankara high-speed railway which has a total length of 533 km was performed with train speed 250 km/h. The measurement was done at Kırkpınar, Sakarya where the SAU Kırkpınar Guest House is located. The purposed test location is near to Arifiye train station. The high-speed railway line passes through the Kırkpınar village which is located at the western end of the place in the Sapanca district. This place was chosen for experimental measurements because of its weak soil condition (V_S = 200 m/s), being close to the train line and away from other environmental vibrations. There are four railway lines near the guest house buildings. These buildings are located just 8-10 m away from the Line 1 as shown in Figure 1. The measurement campaign was carried out in order to determine the free field ground motion produced by repeated train passes. The obtained results of the field measurements are presently used to validate the prediction numerical model. The railway line selected for this purpose is the line L1 which stretches from Istanbul to Ankara.

(a)

(b)

Figure 1: (a) Location of the railway and (b) details of the measurement site

TCDD HT65000 is considered as test train. The train consists of 6 cars but depending on the passenger situation can be reconstructed as 8-car units with two additional cars. There is a set of right and left wheels for each axle and the axle load of the car is 180 kN. The distance between the first and last axle is 21.8 m which in terms of time is 0.314 sec for the considered train with speed of 250 km/h. The distance between the wheels is 2.8 meters. This train is about 159 m in length and human capacity 419. Train is moving over ballasted track which is consists of UIC-60 rails and B70 monoblock sleepers. Characteristics of the train are shown in Figure 2.

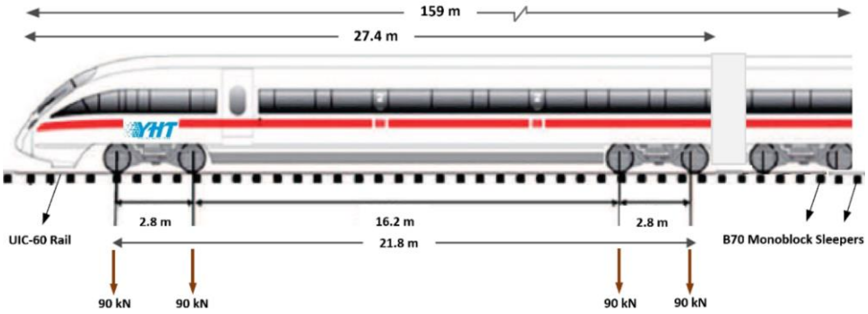
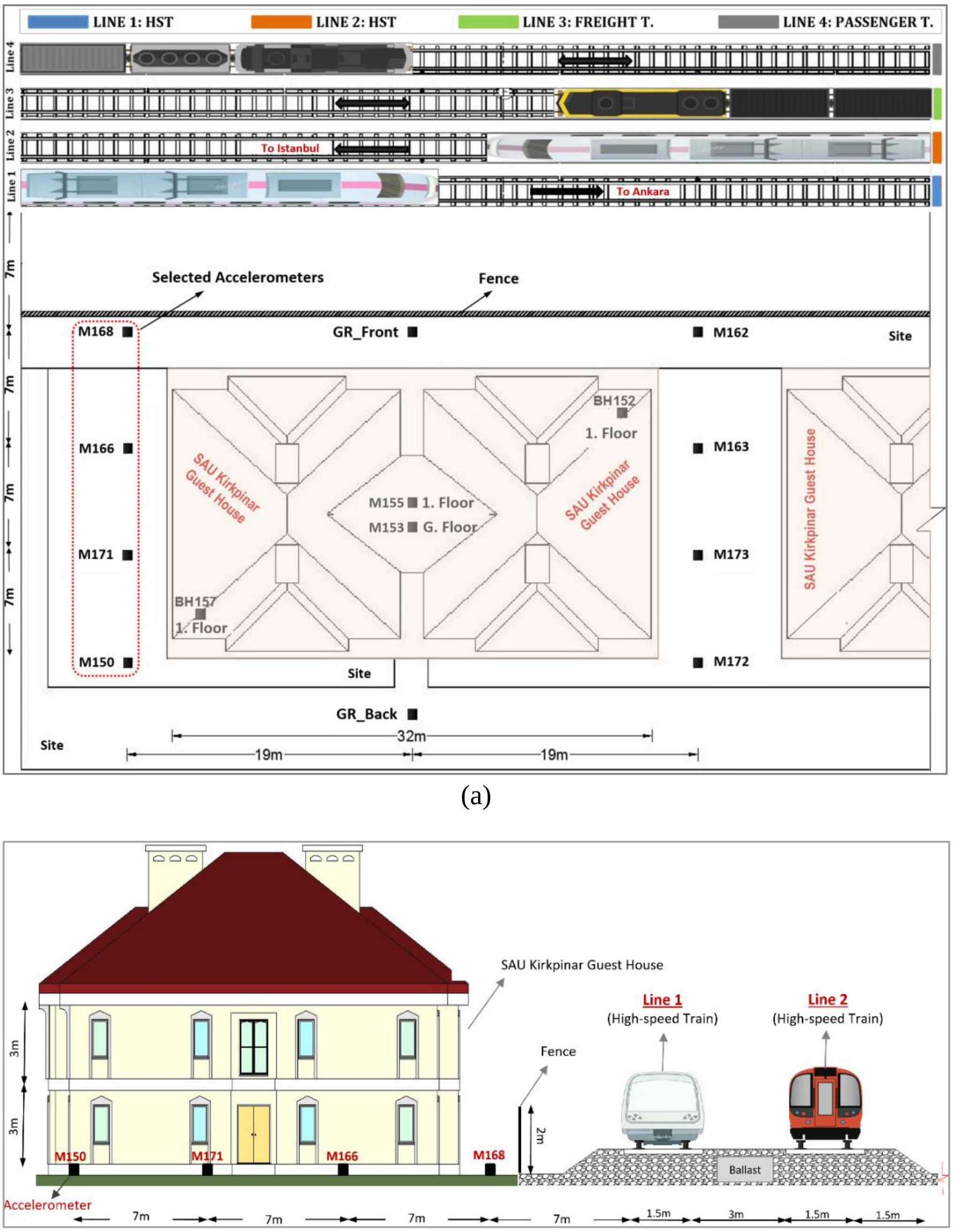


Figure 2: Geometrical characteristics and axle load of train HT65000

3 The in-situ experiment

3.1 Measuring point arrangement

Figure 3 shows the testing instrumentation plan and cross section for the field measurements carried out on July 2018 at Kirkpinar, Sakarya. There are 4 different railway lines in testing site. The ground-borne vibration has been recorded at this site for variety of train passages including passenger trains, freight trains and high-speed HT65000 trains. The lines L1 and L2 are belong to high-speed trains which is connecting Istanbul with Ankara, while the lines L3 and L4 are used for freight transportation and suburban passenger traffic purposes. Measurements have been performed in 14 measuring points in three directions during the passage of trains. The directions are defined as N-S (perpendicular to the track), E-W (parallel to the track) and U-D (vertical downward). Ten of the accelerometers placed on the ground surface to examine free field motion, and other four of them located in the SAU Kirkpinar Guest House building for structural monitoring observations. Passage of trains on all tracks are recorded during measurements. In this study, in order to validate the prediction numerical model, the data from four measurements (M168, M166, M171 and M150) during the passage of HST at 09:40 AM were selected only. These accelerometers were placed at distances 7, 14, 21, and 28 m from the line 1.



(a)

(b)

Figure 3: Schematic diagrams of measuring point arrangement (a) top view and (b) cross-section view

3.2 Recorded passages

Four train passages have been recorded by M168, M166, M171 and M150 accelerometrs in order to observe the ground vibration. These measurements carried out during passages of the high-speed trains (HSTs) on line L1 with speed 250 km/h. The recorded HST passages are summarised in Table 1.

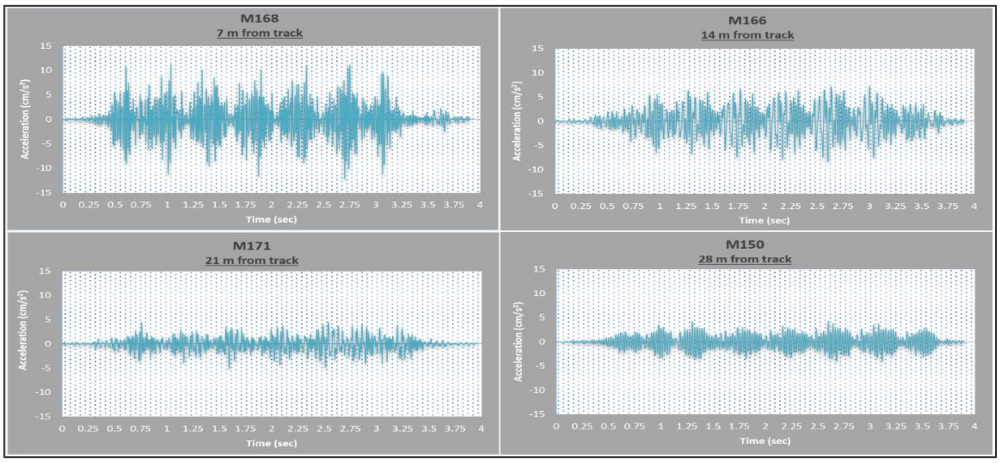
Figure 4: Passage of the HT65000 high-speed train on track 1 with speed V = 250 km/h (Kirkpinar, Sakarya 2018)

Table 1: Overview of recorded high-speed train passages

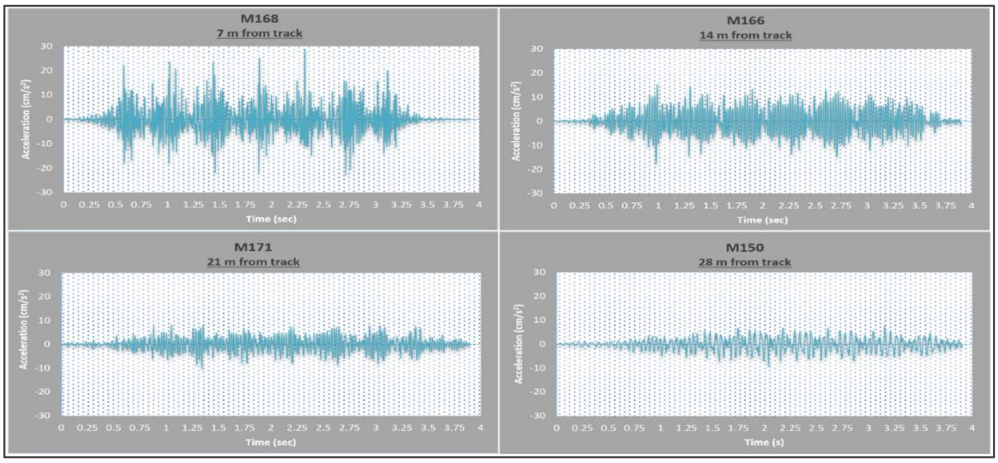
Track	Direction	Passage	Date and time			
			17-07-2018			
1	Istanbul - Ankara	4	09:40	11:04	12:15	13:34

3.3 Field measurement results

In this study, recorded ground vibration during the passage of the high-speed train is prepared in terms of acceleration. In order to transfer raw data to interpretable data, the SeismoSignal program was used for data processing. The measured raw data were base line corrected and the fourth-order Butterworth bandpass filter was applied. The frequency range defined between 10 Hz to 100 Hz. Time-history graphs carried out for both N-S (perpendicular) and U-D (vertical) directions and peak ground accelerations (PGAs) were extracted. Figure 5 summarise the time history of the vertical and parallel accelerations at all distances from the track 1. The extracted peak ground accelerations are given in Table 2.



(a)



(b)

Figure 5: Time-histories of the ground vibration accelerations at 7 m, 14 m, 21 m and 28 m from track during the passage of the HT65000 high-speed train on track 1 with speed of 250 km/h. (a) in horizontal parallel direction and (b) in vertical downward direction

Table 2: Summary of PGA values for parallel and perpendicular directions

Device No	Distance from Track (m)	N-S	U-D
M168	7	0.230	0.307
M166	14	0.078	0.128
M171	21	0.082	0.102
M150	28	0.043	0.031

It is observed from Figure 5 and Table 2 that vibration levels decreased with distance from the track. For perpendicular direction, at $x = 7$ m from the track, the PGA for M168 is equal to 0.230 m/s^2 and at $x = 28$ m from the track, the PGA for M150 is equal to 0.043 m/s^2. When considering the results for vertical direction, at $x = 7$ m, the PGA for M168 is equal to 0.307 m/s^2 and at $x = 28$ m the PGA for M150 is equal to 0.031 m/s^2. According to the results, the distance of railway lines and peak ground accelerations are directly proportional. Also, the PGA results for both directions show that the downward (U-D) direction of train vibrations has more impact than the perpendicular (N-S) direction.

4 The numerical prediction model

4.1 Finite element modeling

In this study, a two-dimensional plane-stain finite element model was developed in PLAXIS 2D using 15 noded triangular elements. The FE model developed in the current study is shown in Figure 6. In dynamic analysis, the model dimensions and boundaries, finite element size, time step and mesh size have to be selected carefully for results accuracy [11-13]. For determining of the finite element model dimensions, many analyses were employed in the past and it is suggested that these boundary areas must be as far at least 8-10 times of the superstructure base width [14, 15]. In the present study, the length of the model was chosen 160 m while the depth was 40 m. Standard fixities and absorbent boundaries were assigned along the model to reduce the wave reflections at the boundaries. The horizontal and vertical sides were fully restrained ($u_x = u_y = 0$). A linear elastic soil model was used due to small deformations induced by the dynamic wave.

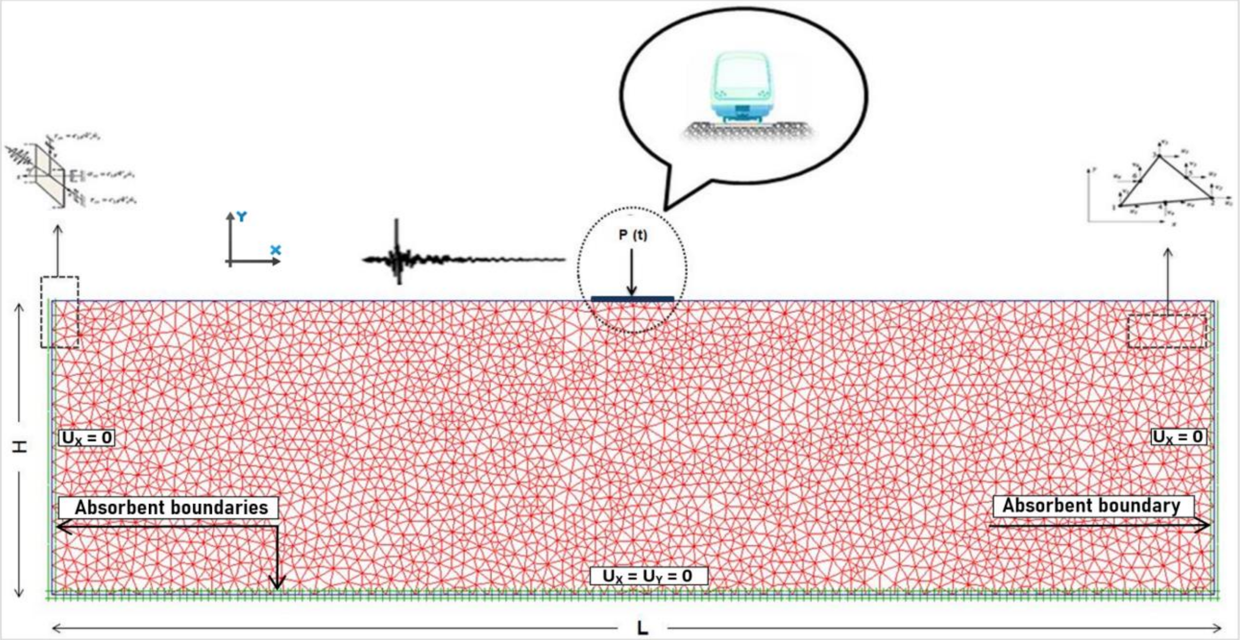


Figure 6: Typical 2D FE model of track-ground system developed in PLAXIS

The relevant properties for soil were density, $\gamma = 16.18$ kN/m^3; modulus of elasticity, $E = 1.38 \times 10^5$ kN/m^2; shear wave velocity, $V_S = 170$ m/s and Poisson's ratio, $\nu = 0.478$. The standard railway superstructure is modelled as one-dimensional (ID) beam element with required moment of inertia and moment of area. As the train load changed in the time and it is not static, therefore the train load is considered as dynamic point load. In the current study, a dynamic point load of magnitude 32.5 kN used in the FE numerical modeling, as shown in Figure 7.

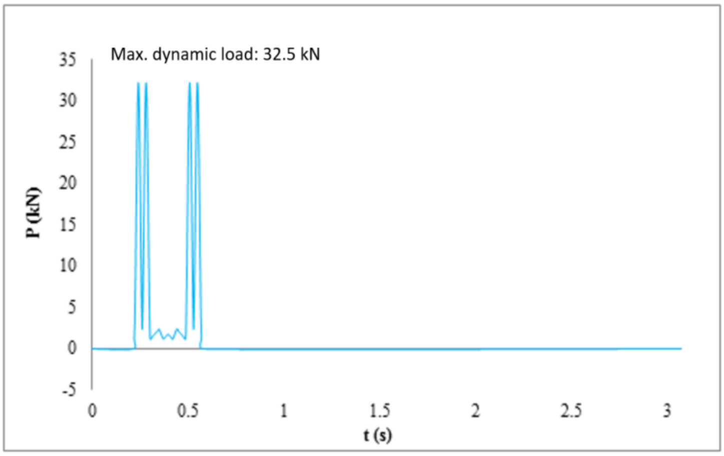


Figure 7: Time-dependent variation of the influence forces for HST passage [16]

4.2 Numerical results

The numerical analysis of the proposed track-ground coupled model for different points has been performed in the time domain under plain-strain condition by using PLAXIS finite element package. In this study, a 2D linear elastic analysis was performed and the relative horizontal and vertical accelerations for point A, B, C and D were prepared in form of diagrams and shown in Figure 9. The peak ground accelerations (PGAs) of the finite element analysis for different points are given in Table 3.

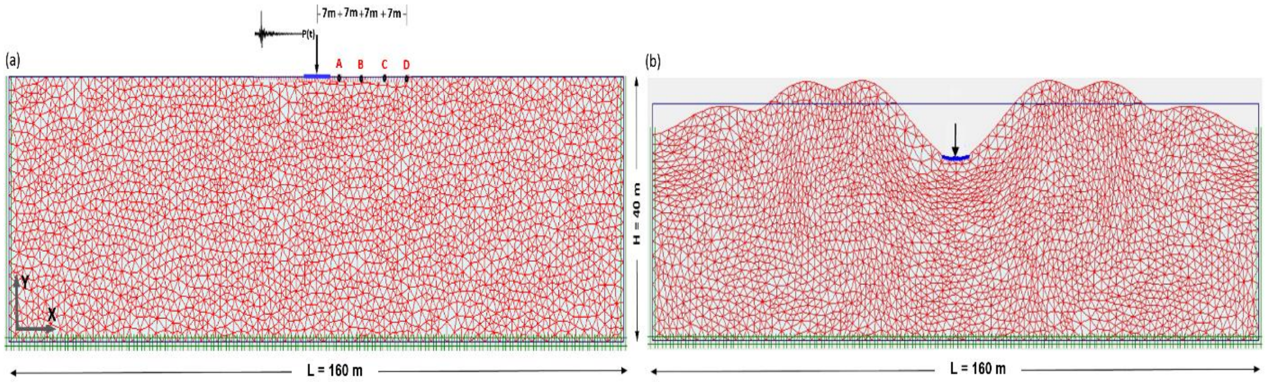


Figure 8: (a) The FE model (before calculation) and (b) deformed mesh (after calculation)

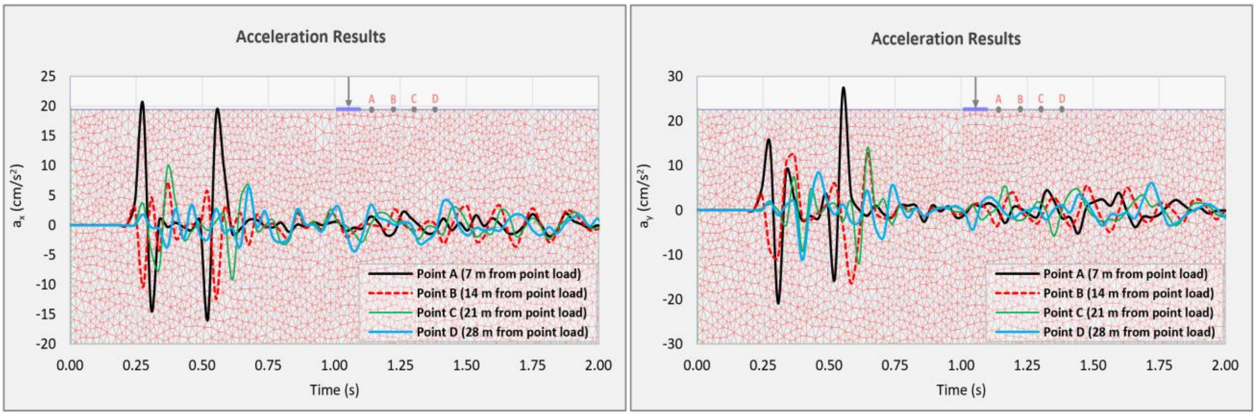


Figure 9: The time history of the horizontal and vertical accelerations at selected points

Table 3: PGA values in horizontal and vertical directions (m/s^2)

Points	Distance from point load (m)	PLAXIS	
		a_x	a_y
A	7	0.204	0.272
B	14	0.125	0.164
C	21	0.096	0.138
D	28	0.064	0.112

Figure 9 shows the horizontal and vertical accelerations (a_x and a_y) for the selected points (see Figure 8a) at distances of x = 7 m, 14 m, 21 m and 28 m from the load axis. Acceleration amplitudes were significantly decreased with distance from the dynamic load as expected. The highest acceleration belongs to checkpoint A which is located near the load axis. The checkpoints B, C and D have smaller accelerations as the distance increase in x direction. From Table 3 it is also observed that, the largest peak accelerations are related to the vibration calculated in the vertical direction whereas the smallest peak accelerations occur in the horizontal direction.

4.3 Validation of present model

The validation of the present numerical model was performed using field measurement data which is carried out by the authors and presented in the previous section. The measured and calculations results were compared for validation by using peak ground acceleration (PGA) values. Figure 11 shows a comparison between measured and calculated peak ground accelerations on the ground at distances 7 m, 14 m, 21 m and 28 m from the track, where a reasonable fit was found (Figure 10). The vertical and horizontal PGAs for selected points are presented and summarised in Table 4. A comparison between the measured and calculated accelerations on the ground shows a good agreement and the compatibility of the results proves that the verified FE model can be applied in the analysis of vibrations.

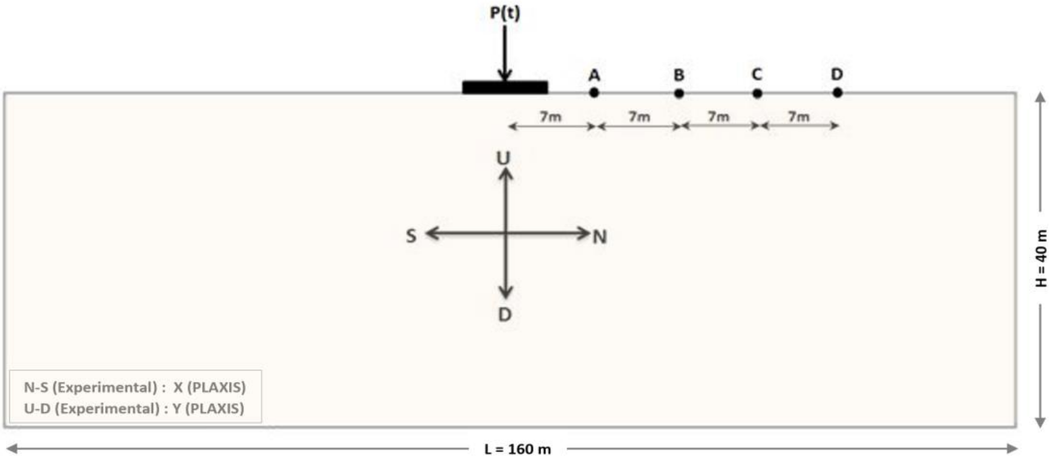


Figure 10: Example of a 2D numerical model

Table 4: Comparing PGA of the measured and calculated accelerations (m/s^2)

Device/measuring point	Distance from track (m)	Experimental		PLAXIS	
		N-S	U-D	a_x	a_y
M168 / A	7	0.23	0.307	0.204	0.272
M166 / B	14	0.078	0.128	0.125	0.164
M171 / C	21	0.082	0.102	0.096	0.138
M150 / D	28	0.043	0.031	0.064	0.112

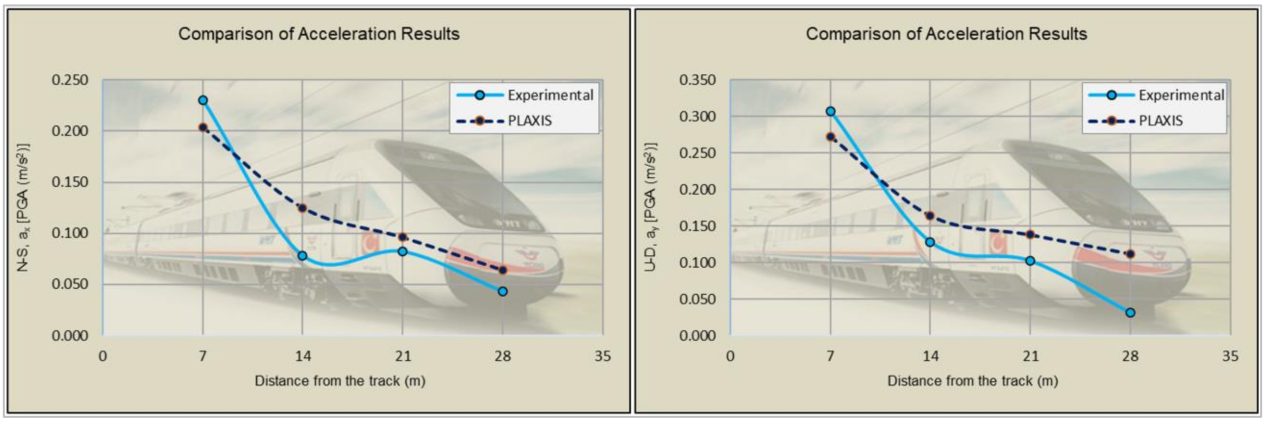


Figure 11: Comparison of measured and calculated peak ground accelerations in horizontal and vertical directions

5 Impact of soil classification on the train-induced vibrations

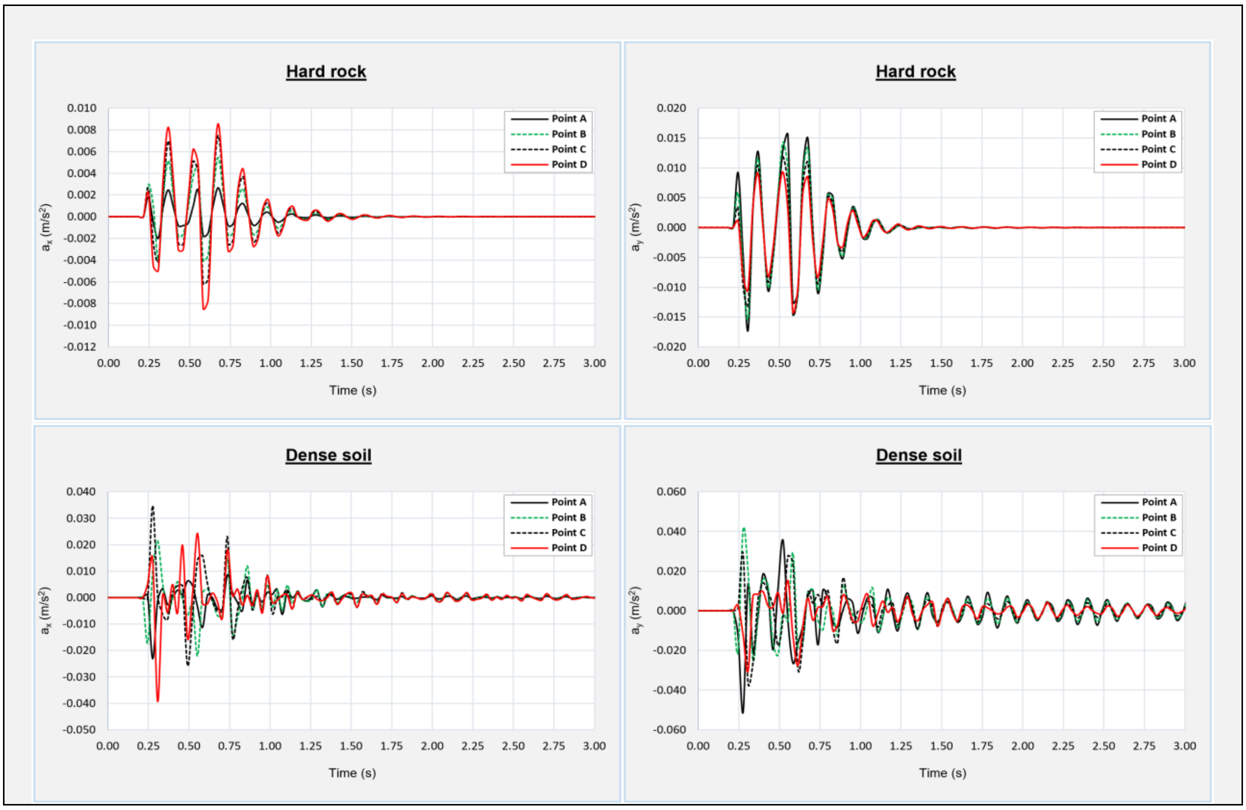
According to the Turkish Building Earthquake Code 2018 (TBEC 2018) [17], rock and soil can be divided into 6 categories, which are hard rock, rock, dense soil, medium-hard soil, soft soil and special soils that requiring site-specific evaluation.

To investigate the effect of soil properties on the train-induced vibrations, analysis was performed for four types of soil. The soils were specified as hard rock, dense soil, medium-hard soil and soft soil. In the present study, a 2D linear elastic analysis was performed and the relative horizontal and vertical accelerations for the selected points (see Figure 8a) were obtained comparatively and showed in graphic forms. The mechanical properties of different soil types are shown in Table 5.

Table 5: Mechanical properties of different soil types

Parameters	Hard rock	Dense soil	Medium - hard soil	Soft soil
γ (kN/m^3)	26.50	21.64	18.64	16.67
E (kN/m^2)	4.5×10^7	3.01×10^6	3.61×10^5	3.45×10^4
υ (-)	0.125	0.35	0.30	0.25
V_S (m/s)	2720	710	270	100

Based on the established FE model and numerical analysis, the resulting time histories and PGA of the vertical and horizontal accelerations on the ground at selected points are carried out and shown in Figure 12 and 13. The extracted peak ground accelerations are given in Table 6.



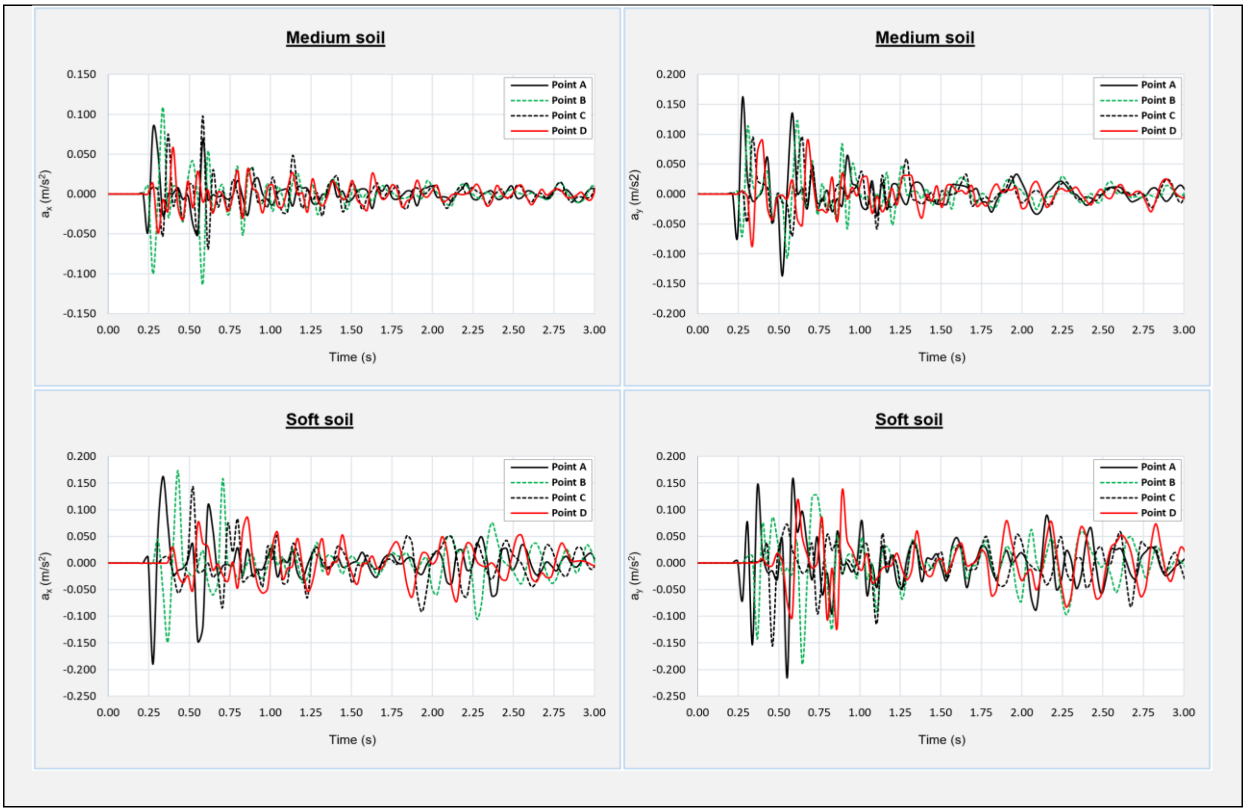


Figure 12: The time history of the horizontal and vertical accelerations at selected points for different soil types

Table 6: Summary of maximum vibration accelerations at different points

Soil Types	a_x (m/s^2)				a_y (m/s^2)			
	A	B	C	D	A	B	C	D
Hard rock	0.003	0.005	0.007	0.009	0.017	0.015	0.014	0.014
Dense soil	0.023	0.022	0.035	0.039	0.051	0.041	0.037	0.030
Medium soil	0.082	0.113	0.098	0.059	0.161	0.123	0.095	0.090
Soft soil	0.190	0.173	0.143	0.086	0.215	0.190	0.156	0.134

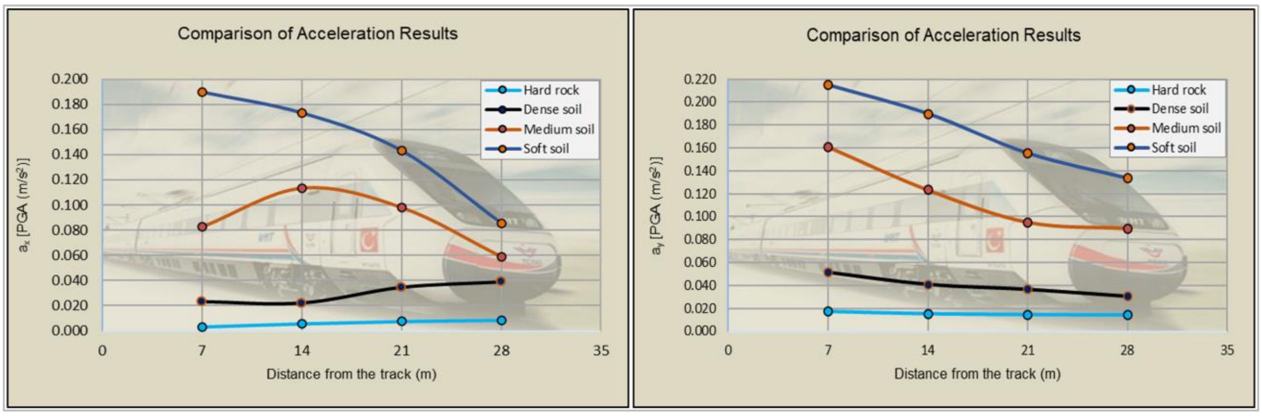


Figure 13. Comparison of calculated peak ground accelerations for different soil types in horizontal and vertical directions

Comparing the maximum accelerations on the ground at the nearest and furthest points to the track (A and D) it can be found that, the maximum horizontal acceleration values for point A on soft soil are respectively 56%, 88% and 98% bigger than medium, dense and hard rock. Also, the maximum horizontal acceleration values for point D on soft soil are respectively 31%, 55% and 89% bigger than medium, dense and hard rock. When considering the results for vertical direction, it can be said that the maximum vertical acceleration values for point A on soft soil are respectively 25%, 76% and 92% bigger than medium, dense, and hard rock. Also, the vertical PGA values for point D on soft soil are respectively 33%, 78% and 89% bigger than medium, dense, and hard rock.

6 Conclusions

An in-situ test for ground vibration due to passage of high-speed train (HT65000) with speed of 250 km/h was carried out on the Istanbul-Ankara high-speed railway in Turkey. During the test, the resulting time histories of the vertical and horizontal accelerations on the ground are obtained. Secondly, a numerical prediction model for train-induced ground vibrations has been developed. The results of in-situ measurements used to validate the numerical model. Lastly, to investigate the effect of soil properties on the train-induced vibrations, analysis was performed for four soil types with different stiffnesses by using verified model. Then, the relative horizontal and vertical accelerations for different soil conditions were obtained comparatively.

The field and numerical results presented in this study revealed that:

(1) The vibration levels decreased with distance from the track. According to the results, the distance of railway lines and peak ground accelerations are directly proportional.
(2) The PGA results for both directions show that, the downward direction of train vibrations has more impact than the perpendicular direction.
(3) According to the results, the provided numerical results show a good agreement with the experimental results. Therefore, the compatibility of the results proves that the verified finite element model can be applied in the analysis of vibrations.
(4) The train induced ground vibrations vary considerably for different soil conditions because of stiffness of soils. It is observed that, the PGA values are increasing from hard rock to soft soil.
(5) The analysis with PLAXIS 2D under different soil conditions demonstrated that, the train-induced ground vibrations for each soil type change according to its mechanical properties.

Acknowledgments

This research is supported by the TUBITAK (The Scientific and Technological Research Council of Turkey) under the grant No: 217M427. Their financial support is gratefully acknowledged.

References

[1] S. Gupta, G. Degrande, G. Lombaert, "Experimental validation of a numerical model for subway induced vibration," *Journal of Sound and Vibration*, vol. 321, no. 12, p. 786–812, 2009.

[2] N. Triepaischajonsak, D. J. Thompson, "A hybrid modelling approach for predicting ground vibration from trains," *Journal of Sound and Vibration*, vol. 335, p. 147-173, 2015.

[3] Y. B. Yang, H. H. Hung, D. W. Chang, "Train-induced wave propagation in layered soils using finite/infinite element simulation," *Soil Dynamics and Earthquake Engineering*, vol. 23, no. 14, p. 263-278, 2003.

[4] G. Lombaert, G. Degrande, "Ground-borne vibration due to static and dynamic axle loads of InterCity and high-speed trains," *Journal of Sound and Vibration*, vol. 319, no. 3-5, p. 1036–1066, 2009.

[5] S. Gupta, W. Liu, G. Degrande, G. Lombaert, "Prediction of vibrations induced by underground railway traffic in beijing," *Journal of Sound and Vibration*, vol. 310, no. 3, p. 608-630, 2008.

[6] H. Xia, J. Chen, P. Wei, C. Xia, G. D. Roeck, G. Degrande, "Experimental investigation of railway train-induced vibrations of surrounding ground and a nearby multi-story building," *Earthquake Engineering and Engineering Vibration*, vol. 8, no. 1, p. 137-148, 2009.

[7] L. Zhang, Q. Feng, "Experimental analysis on ground vibration generated by high-speed train," in *Third International Conference on Transportation Engineering (ICTE)*, p. 1597-1602, Chengdu, China, 2011.

[8] G. Degrande, L. Schillemans, "Free Field Vibrations During the Passage of a Thalys High-Speed Train at Variable Speed," *Journal of Sound and Vibration*, vol. 247, no. 1, p. 131-44, 2001.

[9] E. Çelebi, S. Fırat, G. Beyhan, İ. Çankaya, İ. Vural, O. Kırtel, "Field experiments on wave propagation and vibration isolation by using wave barriers," *Soil Dynamics and Earthquake Engineering*, vol. 29, no. 5, p. 824-833, 2009.

[10] L. Auersch, "The excitation of ground vibration by rail traffic: theory of vehicle–track–soil interaction and measurements on high-speed lines," *Journal of Sound and Vibration*, vol. 284, no. 1-2, p. 103-32, 2005.

[11] V. Galavi and R. B. J. Brinkgreve, "Finite element modelling of geotechnical structures subjected to moving loads," in *VIII ECNUMGE - Numerical Methods in Geotechnical Engineering*, p. 235-240, Delft, Netherlands, 2014.

[12] A. A. Faizan, O. Kırtel, "Dynamic behaviour of railway bridge subjected to different strong ground motions considering soil-structure interaction," in *International Conference on Research in Education and Science (ICRES)*, p. 641-647, Ephesus-Kusadasi, Turkey, 2017.

[13] E. Çelebi, O. Kırtel, "Non-linear 2-D FE modeling for prediction of screening performance of thin-walled trench barriers in mitigation of train-induced ground vibrations," *Construction and Building Materials*, vol. 42, p. 122-131, 2013.

[14] J. M. Rosset, F. Kausel, "Dynamic soil-structure interaction," in *Second International Conference on Numerical Methods in Geomechanics*, p. 3-19, Blacksburg, Virginia, 1976.

[15] A. A. Faizan, "Demiryolu köprülerinin yapı-zemin etkileşimi altında analizi," Master thesis, Dept. Civil Eng., Sakarya University, Sakarya, Turkey, 2017.

[16] F. Göktepe, "Yüksek hızlı trenlerin çevre yapılarda oluşturduğu titreşimlerin önlenmesi için bariyer sistemlerin etkinliğinin parametrik olarak incelenmesi," Ph.D. dissertation, Dept. Civil Eng., Sakarya University, Sakarya, Turkey, 2013.

[17] *Turkish Building Earthquake Code*, TBEC2018, 2018.