

# Measurement of vibrations generated by high speed railway traffic and evaluation according to international norms

S Ates <sup>1\*</sup>, E Celebi <sup>2</sup>, O Kirtel <sup>3</sup>, A C Zulfikar <sup>3</sup>, and F Goktepe <sup>5</sup>

<sup>1,2</sup> Department of Civil Engineering, Sakarya University 54187 Esentepe Campus/Sakarya/TURKEY

<sup>3</sup> Department of Civil Engineering, Sakarya University of Applied Sciences 54187 Esentepe Campus/Sakarya/TURKEY

<sup>4</sup> Department of Civil Engineering, Gebze Technical University, 41400 Cayirova Campus/Kocaeli/TURKEY

<sup>5</sup> Department of Civil Engineering, Bartin University, 74100 Bartin/TURKEY

\*Email: sami.ates@ogr.sakarya.edu.tr

**Abstract.** High-speed trains are one of the most preferred ways of transportation. The fact that it is fast and safe, cost effective and not being effected by weather conditions provides many advantages for passengers but there are also many disadvantages for the buildings close to the train track and the people who reside in these buildings. In this study, a series of site tests were performed to obtain the acceleration recordings of the vibrations existing in free field of the soil and building foundation. The average shear wave velocity of soil was considered as 200m/s and the velocity of the high-speed train was taken as 250km/h. In this study, it is aimed to reveal the kinematic interaction between the free field motion and foundation vibration of the building while high-speed train passed. Furthermore, vibrations occurring under the current soil conditions of the study area were evaluated according to the key parameters defined in regulations of the Federal Transit Administration Report (FTA) and Human Exposure to Vibration in Buildings/Effects of Vibration on Structures (DIN 4150-2/3). It is seen that the compliance with the limit values specified in the regulations changes according to the purpose of use. The results showed that rigid foundations significantly modify the wave propagation and vibration level due to kinematic interaction effects.

## 1. Inyroduction

High-speed railways in Turkey are designed with a maximum speed of 250-300km/h and a maximum axle load of 22.5 tons. High-frequency vibrations produced by high-speed trains during railway crossings are spread to the nearby surroundings via the underlying soil. The train induced ground-born vibration energy is dissipated in the soil medium and affects the structures close to the railway track by vibrating. It is well known that the considerable portion of the vibration energy is transmitted by Rayleigh surface waves with undesirable effects [1-2]. These high amplitude environmental oscillations not only damage nearby buildings and their foundations, but also affect human comfort level with its unfavorable shaking. It is seen that the vibrations spread from the train lines passing through the densely residential district exceed the acceptable limits given for nearby structures in regulations in terms of human comfort and building health. Therefore, the problem of train induced high level vibrations



associated with the dynamic soil-structure interaction and wave propagation is remarkable issue to be handled from to point of reducing structural vibrations, determining how far the structure should be built from the railway line, eliminating the adverse effects related with strong ground motion in near environment, and knowing what precautions should be taken to provide for building safety, human health and comfort. For this purpose, several experimental studies on in-situ have been carried out to measure the environmental and structural vibrations [1-3]. The importance of this type of geo-dynamic problem increases especially in weak soil deposits for constructions.

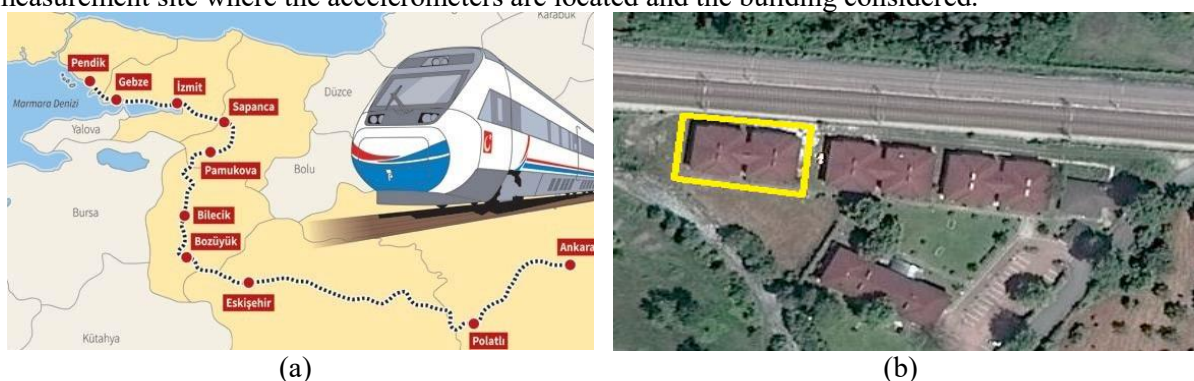
The goal of this study is to investigate the acceptability level of high-speed train traffic induced structural vibrations in densely populated area and to assess the recorded vibration data according to the threshold values of the international norms given [4-6]. Furthermore, the effect of the kinematic interaction on free field motion caused by the rigidity of the building foundation is examined experimentally by comparing the obtained response spectrum curves. It is intended to determine the characteristics of the soil-structure interaction problem with field tests and to provide the necessary information infrastructure for the measures that can be taken to ensure that the vibration level limit values specified in international regulations are not exceeded. The transfer functions are derived from the measurements to better understanding the effect of soil-structure interaction, especially in soft ground conditions. With the help of the data obtained from the free field vibration and basement motion of the considered building, it is thought that this function will allow us to estimate the vibration level that may occur in the structure and location where a new building will be constructed near the train line can be determined more appropriately.

## 2. Research method

In this study, field tests were performed by using high performance seismometers which have 32-bit high resolution and have 120 decibel (dB) dynamic range with built in (Global Positioning System) GPS antenna to measure the vibrations radiated from the railway to the environment. The accelerations are recorded by data loggers inside seismometers for assessing the ground motion and structural vibration generated by repeated train crossings, taking into account the local soil conditions where the high-speed train line passes. This location was chosen because of the soft soil conditions as well as the structures close to the train line. During the site measurement, the accelerations of the high-speed trains were recorded at different times and the vibrations were monitored repeatedly. The test location was selected near the Arifiye station of the Istanbul-Ankara high-speed train line with a total length of 533 km. The average shear wave velocity of the test area was measured as 200m/s. The speed of the passing trains during the field measurements was determined to be 250 km/h. The test site is located in the social facility of the Sakarya University of Applied Sciences, just 8-10 m from the railway line, as shown on the Figure 1.

### 2.1. Location of the investigated region

As illustrated in Figure 1a, the high-speed railway line focused on this study passes through the village of Kırkpınar at the western end of the place in the Sapanca District. The Figure 1b shows the measurement site where the accelerometers are located and the building considered.

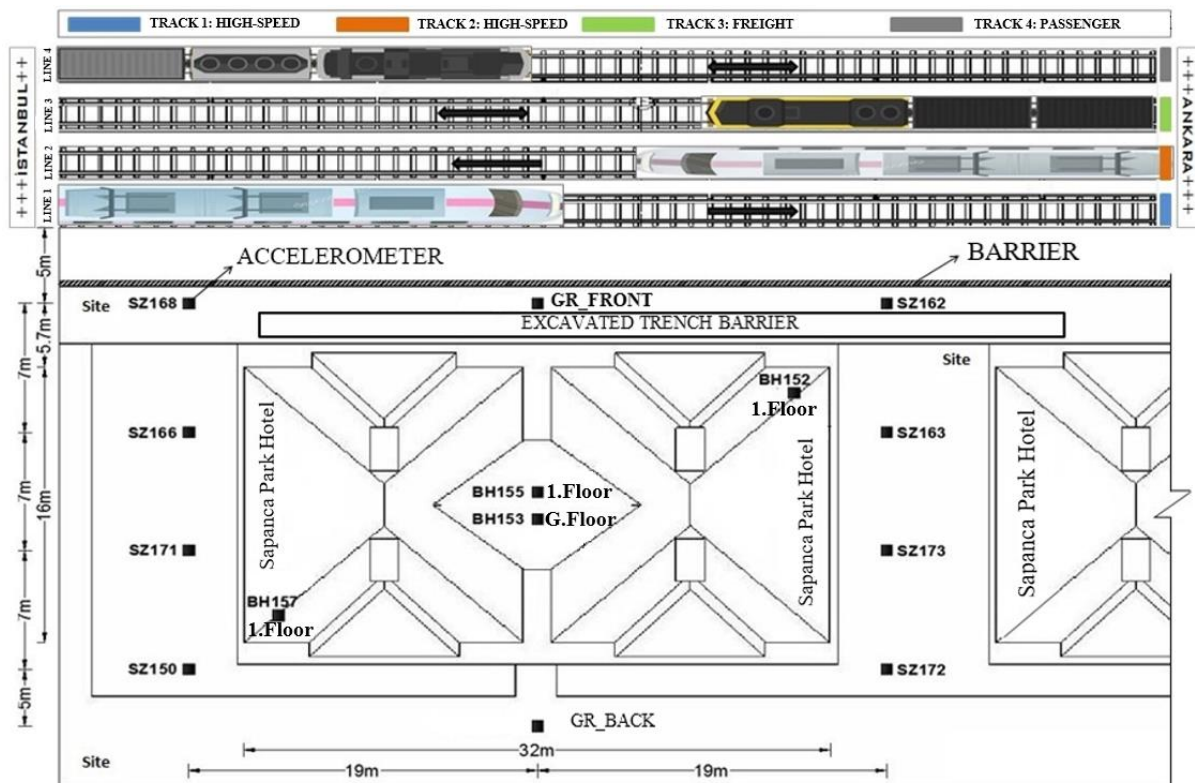


**Figure 1.** Location of the railway line (a) and testing site (b)**Figure 2.** Field view and installation of accelerometers.

### 2.2. Layout of the experimental site

The position of the accelerometers in the working area is shown in Figure 3 along with their distance. There are four different railway lines in experimental site. Two of them denoted as the line 1 and the line 2 belong to high-speed trains. While line 1 connects the direction between Istanbul and Ankara, line 2 serves the route of Ankara-Istanbul. Railway lines defined as 3 and 4 is used for freight transportation and suburban passenger traffic. A total of 12 accelerometers were installed in the test field, 8 of which were placed to observe ground vibrations and 4 to monitor structural vibrations at the basement and first floor of the building considered. In order to reveal the effects of kinematic interaction, which is an important component of the dynamic soil-structure interaction, on free field motion, devices with the designations SZ173 and BH153 were placed in the research area (Figure 3).





**Figure 3.** The layout of testing site and instrumentation

### 2.3. General information of train records

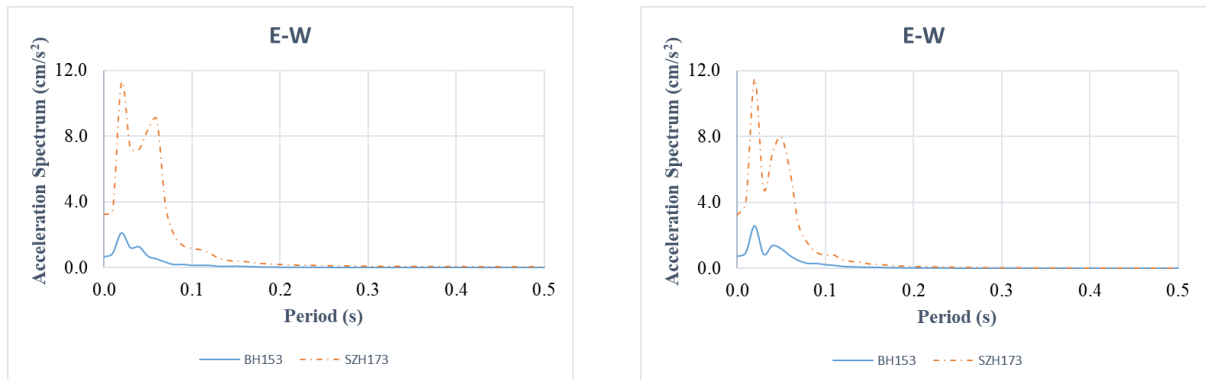
The timetable for repeated train crossings is given in the Table 1 below with the device numbers on which the vibrations are recorded. Structural vibrations recordings in the building are realized by accelerometers identified as BH153 and BH155, while free ground excitations are measured by instruments coded as SZ168 and SZH173.

**Table 1.** Timetable for repeated train passes.

Device No	2. Track	1. Track
SZ168	10:11	11:04
BH153	10:11	11:04
BH155	10:11	11:04
SZH173	10:11	11:04

### 2.4. Analysis of in-situ measurements

**2.4.1 Kinematic Interaction:** The data obtained from SZ173 and BH153 instruments were compared to investigate the kinematic interaction problem. The raw data obtained from the devices were transformed into interpretable data with the help of computer-aided software program such as SeismoSignal. Of all the data recorded by the device on observation point, only the 15-second train transit time was considered. This part of data recorded was opened in SeismoSignal, first aligned (calibrated) to the zero line which is called as baseline correction, then a Butterworth-type filter was applied to the vibration in the frequency range of 10 to 100 Hz to remove the ambient noise vibration. Finally, acceleration spectrum curves were obtained using processed time histories on free ground surface and structure. All analyses were carried out separately for vibrations propagating parallel and perpendicular to the train line during the passage of trains. Response spectra and transfer functions obtained from acceleration time histories are given in Figures 4-6 for two different times of train transitions.

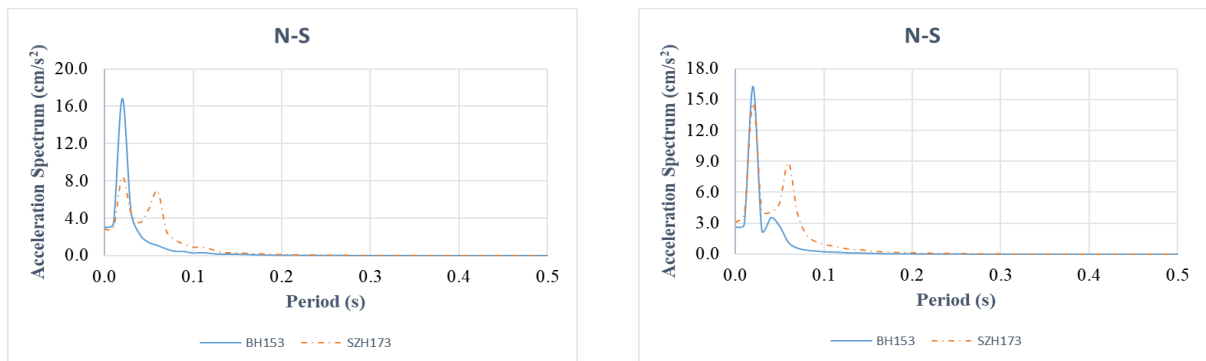


(a) Train at 10.11

(b) Train at 11.04

**Figure 4.** Acceleration spectra for parallel to the railway.

When the measurement results obtained at different times are compared, it is clear seen that kinematic interaction in the parallel direction reduces the vibration level of the free field motion. As shown in Figure 4, the peak acceleration values for both recording times decreased for buildings with natural periods of 0.25 seconds from 11cm/s<sup>2</sup> to 3cm/s<sup>2</sup>.

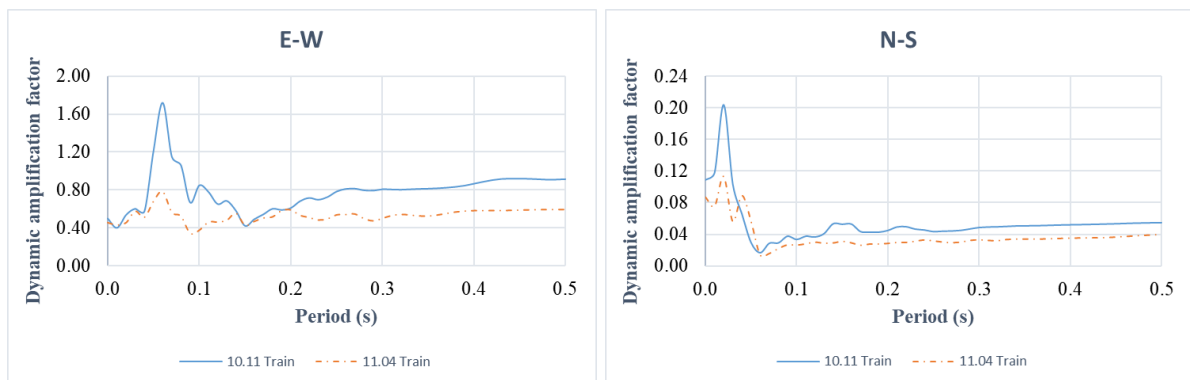


(a) Train at 10.11

(b) Train at 11.04

**Figure 5.** Acceleration spectra for perpendicular to the railway.

It is even seen in Figure 5 for both recording times that the kinematic interaction in the perpendicular direction increases the vibration level of free field motion.



(a) Parallel to the Line

(b) Perpendicular to the line

**Figure 6.** Transfer functions.

The discrepancy of the transfer functions for two different transit times of trains that directly indicate the kinematic interaction effect in the considered direction to the train line is shown in Figure 6a-b.

### 2.4.2 Evaluation of the vibration data according to regulations

2.4.2.1 *Federal Transit Administration (FTA)*: Decibel notations are employed for assessing the vibration level according to the FTA criteria. Root Mean Square (RMS) values were achieved by taking the square root of the mean squares of the amplitude of the velocity values after the raw data were processed and the acceleration data were transferred to the velocity data. The maximum RMS value can be calculated as follow,

$$L_v = 20 \log \left( \frac{v}{v_{ref}} \right)$$

where  $v$  is the maximum RMS amplitude in m/s and the  $v_{ref}$  is the reference velocity amplitude taken as  $2.54 \times 10^{-8}$  m/s. The obtained velocity level is evaluated in terms of threshold values in the regulations for human response and structural damage are given in Table 2 and 3, respectively.

**Table 2.** Threshold vibration speed levels in the regulation for human perception.

Vibration Velocity Level	Human Response
65 VdB	Approximate threshold of perception for many humans. Low-frequency sound usually inaudible. Mid-frequency sound: excessive for quiet sleeping areas.
75 VdB	Approximate dividing line between barely perceptible and distinctly perceptible. Many people find transit vibration at this level annoying. Low-frequency noise: tolerable for sleeping areas. Mid-frequency noise: excessive in most quiet occupied areas.
85 VdB	Vibration tolerable only if there are an infrequent number of events per day. Low-frequency noise: excessive for sleeping areas. Mid-frequency noise: excessive even for infrequent events for some activities.

**Table 3.** Regulation Limit Values for Building Damage

Land Use Category	Ground-Borne Vibration and Noise Impact Criteria			
	Ground-Borne Vibration Impact Levels (VdB re 1 micro inch/sec)		Ground-Borne Vibration Impact Levels (dB re 20 micro Pascals)	
	Frequent <sup>1</sup> Events	Infrequent <sup>2</sup> Events	Frequent <sup>1</sup> Events	Infrequent <sup>2</sup> Events
<b>Category 1:</b> Buildings where vibration would interfere with interior operations.	65 VdB <sup>3</sup>	65 VdB <sup>3</sup>	N/A <sup>4</sup>	N/A <sup>4</sup>
<b>Category 2:</b> Residences and buildings where people normally sleep.	72 VdB	80 VdB	35 dBA	43 dBA
<b>Category 3:</b> Institutional land uses with primarily daytime use.	75 VdB	83 VdB	40 dBA	48 dBA

**Notes:**

1. *Frequent Events* is defined as more than 70 vibration events per day.
2. *Infrequent Events* is defined as fewer than 70 vibration events per day.
3. This criterion limit is based on levels that are acceptable for most moderately sensitive equipment such as optical microscopes. Vibration-sensitive manufacturing or research will require detailed evaluation to define the acceptable vibration levels. Ensuring lower vibration levels in a building often requires special design of the HVAC system and stiffened floors.
4. Vibration-sensitive equipment is not sensitive to ground-borne noise.

The transformed measurement data of train passage at 10.11 for the evaluation criteria defined in the FTA are summarized in Table 4.

**Table 4.** Transformed measurement data for evaluation criteria defined in FTA of train passage at 10.11

Device No	Max RMS		Max Velocity (mm/s)		Max Lv (VdB)	
	E-W	N-S	E-W	N-S	E-W	N-S
SZ168	0.175	0.200	0.248	0.283	76.782	77.935
BH153	0.014	0.069	0.020	0.098	54.870	68.682
BH155	0.020	0.071	0.029	0.100	57.989	68.901

The data obtained from the SZ168 device at 10.11 for train passage shows that the vibration level in parallel and perpendicular direction to the train line exceeds the limit values of the regulation for human perception as indicated in Table 4. When the structural vibration measured with BH153 and BH155 accelerometers are compared with the criteria values specified in the regulation, it is seen that the vibration velocity level exceeds the threshold values only in the perpendicular direction to the railway line.

Regarding the regulation for structural damage (Table 3), the data obtained from SZ168 device indicate that the vibration level exceeds the acceptable values in parallel and perpendicular direction to the train line for the land use category 1 in the case of infrequent events. Likewise, when considering the records monitored from BH153 and BH155 devices, the vibration level does not exceed the regulation limit values parallel to the train line in terms of structural damage for land use category 1. However, the same situation cannot be mentioned for other vibration direction as shown in Table 4.

**Table 5.** Transformed measurement data for evaluation criteria defined in FTA of train passage at 11.04.

Device No	Max RMS		Max Velocity (mm/s)		Max Lv (VdB)	
	E-W	N-S	E-W	N-S	E-W	N-S
SZ168	0.189	0.218	0.268	0.308	77.440	78.667
BH153	0.020	0.052	0.028	0.074	57.774	66.289
BH155	0.032	0.049	0.045	0.070	62.015	65.745

The converted measurement results for the evaluation criteria defined in the FTA for the train passage at 11.04 are shown in Table 5. The same results concerning human perception and structural damage were obtained when the vibration recordings were also evaluated for this transition time of high-speed trains.

*2.4.2.2 Human Exposure to Vibration in Buildings/Effects of Vibration on Structures (DIN 4150-2/3)* In order to make a comparison with the limit values defined in this German standard, it is necessary to obtain the frequency content of the vibration records, especially the dominant frequency of the dynamic source which is obtained by Fast Fourier Transform depicted in Figures 7-10. The dominant frequency and maximum speed values of the measured records were compared with the limit values in the DIN4150 as given in Tables 6-9. Evaluation criteria for human health and comfort according to DIN 4150-2 are given in Table 6.

**Table 6.** Threshold vibration speed levels in the regulation for human perception.

Approximate Vibration Level	Degree of Perception
0.1 mm/s	Not felt
0.15 mm/s	Threshold of perception
0.35 mm/s	Barely noticeable
1.0 mm/s	Noticeable
2.2 mm/s	Easily noticeable
6 mm/s	Strongly noticeable
14 mm/s	Very strongly noticeable

Evaluation criteria for structural damage according to DIN 4150-3 are given in table 7.

**Table 7.** Regulation limit values for building damage.

Type of Structure	Vibration Threshold for Structural Damage, PPV (mm/s)				
	Short-Term			Long-Term	
	At Foundation			Uppermost Floor	Uppermost Floor
	0 to 10 Hz	10 to 50 Hz	50 to 100 Hz	All Frequencies	All Frequencies
<b>Commercial /industrial</b>	20	20 to 40	40 to 15	40	10
<b>Residential</b>	5	5 to 15	15 to 20	15	5
<b>Sensitive/Historic</b>	3	3 to 8	8 to 10	8	2.5

The measured peak velocity values parallel to and perpendicular to the train line are given in Table 8 for transition time at 10.11 of high-speed train.

**Table 8.** Speed values obtained from acceleration data at 10.11 of train.

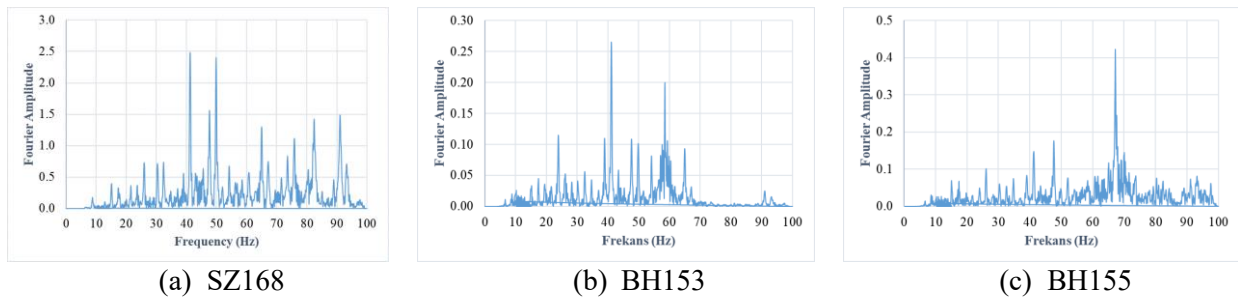
Device No	Max Velocity (mm/s)	
	E-W	N-S
SZ168	0.248	0.283
BH153	0.020	0.098
BH155	0.029	0.100

Table 9 summarizes the peak velocity values parallel to and perpendicular to the train line obtained from the acceleration time history for passage time at 11.04 of high-speed train.

**Table 9.** Speed values obtained from acceleration data at 11.04 of train.

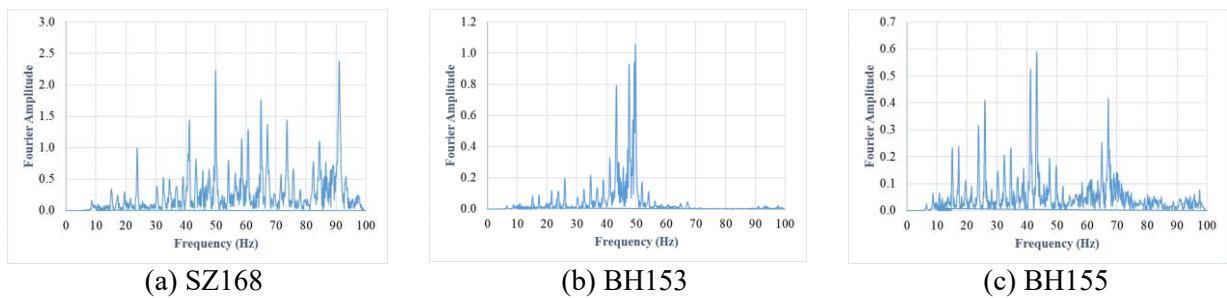
Device No	Max Velocity (mm/s)	
	E-W	N-S
SZ168	0.268	0.308
BH153	0.028	0.074
BH155	0.045	0.070





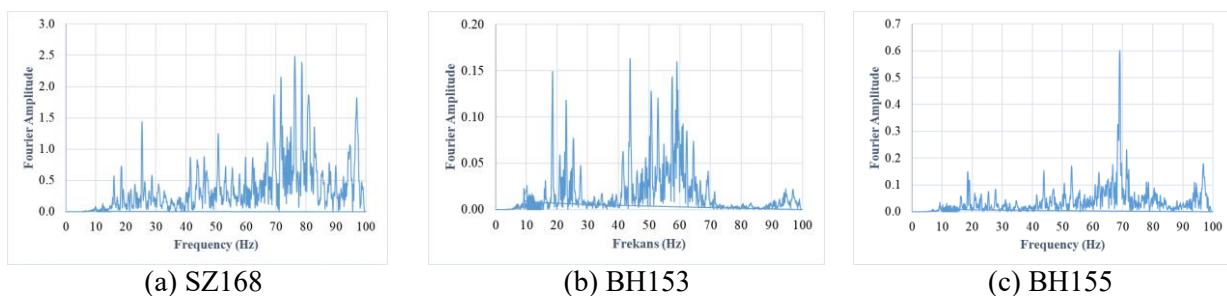
**Figure 7.** Fourier amplitudes parallel to the railway at 10.11 of train.

Evaluating the frequency content of the vibration recordings in the parallel direction to the railway shown in Figure 7, the dominant frequencies are determined as 41 Hz, 42 Hz and 68 Hz, for accelerometers defined as SZ168, BH153 and BH155, respectively. When the vibration record of SZ168 is examined in terms of structural damage, it is seen that the measured maximum velocity does not exceed the acceptable limit value given in the regulation. Furthermore, the data obtained from BH153 and BH155 devices do not exceed the regulation limit values in parallel direction to the train line according to the dominant frequency indicated in Figure 7b-c.



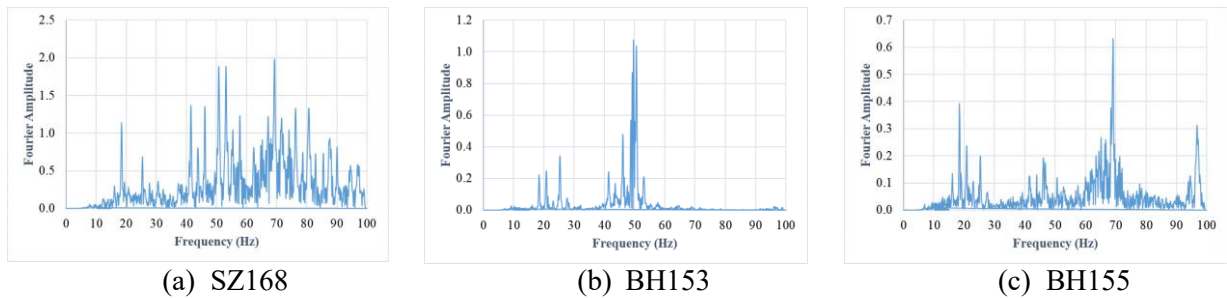
**Figure 8.** Fourier amplitudes perpendicular to the railway at 10.11 of train.

Reviewing the frequency content of the vibration recordings in the perpendicular direction to the railway illustrated in Figure 8, the dominant frequencies are observed as 91 Hz, 50 Hz and 43 Hz for accelerometers denoted as SZ168, BH153 and BH155, respectively. Herein, it is seen that the limit values are not exceeded for the vibration data received at all measuring points in terms of structural damage.



**Figure 9.** Fourier amplitudes parallel to the train line at 11.04 of train.

As shown in Figure 9, the Fourier amplitudes are obtained by using Fast Fourier Transform as 77 Hz, 42 Hz and 69 Hz for all measurement devices. In terms of structural damage, the acceptable velocity values of the regulation is not exceeded in the parallel direction to the railway of the high-speed train for all considered observation points.



**Figure 10.** Fourier amplitudes perpendicular to the train line at 11.04 of train.

Examining the Fourier response of the vibration records for assessing the threshold values given in regulation, measured vibration level in both direction of the test field doesn't make any favourable effect on human comfort and building safety.

### 3. Conclusions

Turkey has launched a high-speed railway transport to be completed until 2023 and ten thousand km high-speed railway line is planned. The increase in the high-speed rail network has made the passage of urban area inevitable. With the increase of train traffic in urban environments, the vibration effects propagating to the densely populated residential district during the train passing have come out as a problem. In this study, various field studies have been conducted to observe the vibration effects of high-speed trains. Structural and non-structural vibration recordings were analysed. The following results are inferred from the analysis results:

- It was observed that the effect of kinematic interaction on free field vibration caused by the rigidity of the building foundation was different in both directions.
- Analysing the obtained vibration data, it was concluded that the vibration effects that propagate in parallel and perpendicular directions during the high-speed train passing are different and therefore vibration measurements should be performed in all directions.
- When vibration measurement results are compared according to the criteria given in terms of human comfort in international standards;
  - when FTA is considered, it is seen that vibration on the free field can be perceived at a disturbing level, but the vibration in the structure is below the threshold value in terms of human response.
  - when the same measured data are evaluated according to DIN4150-2, it is observed that the free ground motion is above the threshold of perception but it cannot be felt inside the structure.
- When vibration records are evaluated according to the criteria given in terms of structural response in international standards;
  - according to FTA, the vibration effects propagated in the parallel direction to the train line remained under the acceptable limit for moderately sensitive equipment, but the vibration effects propagated in the direction perpendicular to the train line exceeded this level,
  - Considering the DIN4150-3, all vibration effects were observed to be under the defined threshold levels.

### Acknowledgement

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