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Parametric study on the impact of traffic-induced vibrations on residential structures in Istanbul, Turkey

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Abstract. Traffic-induced vibrations (TIVs) possess the potential to induce structural damage in both historical and critical edifices. Recent investigations have underscored the adverse impact of TIVs within buildings, manifesting as a deleterious influence on the quality of life and operational efficiency of occupants. Consequently, these studies have dichotomized TIVs into two primary limit categories: the threshold for vibrations capable of causing structural damage and the limit values associated with human comfort. In this current research endeavor, an exhaustive analysis of peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and the frequency spectrum of ground motions originating from diverse traffic sources has been conducted. Furthermore, the detrimental repercussions of these vibrations on structures, gauged through the assessment of the peak particle velocity (PPV) parameter, have been systematically evaluated. The findings of this study elucidate that TIVs within the examined structures do not attain magnitudes conducive to structural compromise; however, the levels surpassing human comfort limits are evident, attributable to specific sources and distances. Moreover, this investigation sheds light on the absence of comprehensive criteria and guidelines pertaining to the assessment of TIVs in structures within the Turkish Building Seismic Design Code 2018. It seeks to raise awareness among building constructors about the critical importance of addressing this issue, emphasizing the imperative for guidelines in mitigating the impact of TIVs on both structural integrity and human well-being.

Keywords: fourier spectrum; human comfort limits; peak particle velocity; traffic-induced vibrations

1. Introduction

The global landscape is witnessing a surge in extensive construction activities adjacent to traffic arteries, propelled by rapid urbanization. These structures, situated close to traffic corridors, are susceptible to Traffic-Induced Vibrations (TIVs), which can impart deleterious effects on their integrity. TIVs emanating from prolonged usage of heavy equipment, or the passage of heavy traffic represent a formidable concern for structures in numerous countries (Seidler *et al.* 2023, Chik *et al.* 2023). The reduction in the source-field distance intensifies TIVs, reaching critical thresholds that demand attention (He *et al.* 2022, Zou *et al.* 2017).

The prolonged exposure of structures to vibrations, whether arising from extended usage of

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heavy equipment or the passage of heavy traffic, poses a noteworthy challenge globally (Li *et al.* 2023a). Even if these vibrations induce only minor structural damage, their persistence may instigate fatigue and overstress issues in the future (Hu *et al.* 2023, Javaid *et al.* 2023). Vibrations encountered by structures originate from both internal and external sources. Internal sources encompass elevators, heating systems, ventilation systems, and mechanical devices, while external sources span earthquakes, wind, explosions, construction activities, and traffic.

Research conducted on TIVs underscores that while these vibrations may not pose an immediate risk of structural damage, they significantly disrupt the comfort of occupants (Li *et al*. 2023b, Kouroussis *et al*. 2014). The impact of TIVs on structures is contingent upon factors such as vibration amplitude and the concurrent density of elements like drilling, pile driving, dynamic compaction, operational activities, and the use of heavy equipment. Studies emphasize that key determinants of TIVs encompass road surface types, vibrations induced by vehicle speed, vehicle types, and traffic volumes (Wang *et al*. 2023, Li *et al*. 2023c, Hashad 2016).

According to Hao *et al*. (2001), a comprehensive analytical investigation has been conducted on diverse buildings, focusing on the nuanced variations of parameters such as velocity, acceleration, and displacement induced by TIVs. Notably, another research endeavor has revealed that historical buildings subjected to TIVs exhibit vulnerabilities, manifesting in specific points of structural damage (Poovarodom *et al*. 2023). A further experimental study by Crispino and D'apuzzo (2001) on a historical building in Naples meticulously measured TIVs at multiple locations, considering various parameters, and subsequently compared the findings against established threshold limits. Moreover, certain devices employed in hospitals and scientific research centers have demonstrated a pronounced sensitivity to these vibrations.

The analysis of TIVs is inherently fraught with uncertainties, encompassing factors such as source-field distance, soil types, and the dynamic characteristics of structures. Dikmen et al.'s (2016a) study, for instance, measured vibration data induced by traffic noise at various distances, estimating kappa soil values based on this information. Subsequently, the study compared these kappa soil values derived from earthquake records in the same region. Similarly, an analogous study delved into the characterization of traffic records obtained at different distances, specifically in far-field and near-field conditions (Dikmen *et al*. 2016b). Furthermore, extensive research efforts focus on the reduction or prevention of traffic-related vibrations, with numerous studies and reports addressing this critical aspect (Xu *et al*. 2023).

Persson *et al*. (2017) conducted a study examining different building types (wooden and concrete structures), assessing changes in absolute velocity-frequency graphs in ground and roof floors in response to variations in floor thickness and type. Vladimir and Ilya (2017) explored vibrations in residential buildings arising from underground traffic, scrutinizing the flow process and alterations in vibration waves. Transfer factor values were provided to estimate vibration levels within the structure, enabling the extrapolation of potential vibrations in other structures with similar systems exposed to underground traffic.

Additionally, a study by Lopes *et al*. (2016) investigated TIVs due to subway operations, examining velocity-frequency values through numerical and experimental analyses across different structural levels. These collective efforts contribute to a comprehensive understanding of TIVs and form a substantial body of knowledge essential for addressing the challenges posed by TIVs in various structural contexts.

Numerous standards and reports exist for the assessment of TIVs in buildings, revealing substantial variability and diverse evaluation criteria, often based on velocity and acceleration parameters or their derivatives (BS 6472 1992, DIN 4150-2 1992, ISO 2631-1 1997, ISO 2631/2

1989, SN 640 312 1978, BS7385-2 1993, DIN 4150-3 1999). The impact of vibrations within structures is detrimental to the quality of life and working efficiency of occupants, prompting the establishment of limits contingent upon the magnitude of vibrations. Standards generally emphasize two key state points: the primary consideration being the human comfort limit level, with structural damage limits also factored in if vibrations surpass a certain threshold. Notably, more stringent limits are stipulated where sensitive equipment or tasks are involved. For instance, considering the Peak Particle Velocity (PPV) parameter, 50 mm/s is defined as the upper limit for vibrations causing damage to concrete structures due to TIVs.

Standards such as BS 6472 outline human comfort limit values for distinct building groups based on velocity and acceleration parameters, a trend similarly observed in codes like DIN4150-2, ISO 2631-1, and ISO 2631-2. Analysis of standards like BS7385-2, German standards DIN4150-3, and Swiss standards SN640 312a reveals specific limit values geared toward assessing the potential occurrence of structural damage resulting from vibrations induced by any source. Discrepancies among standards are evident in the evaluation of vibration magnitudes, particularly in the assessment of structural damage limits, where specific frequency ranges dictate limit values.

Beyond standards, a multitude of reports, recommendations, guidelines, and studies contribute to the body of knowledge surrounding TIVs (Shiferaw *et al.* 2023, Khan *et al*. 2023, Lazi *et al.* 2023). In the Turkish context, a regulatory gap is identified concerning the evaluation of TIVs on structures.

When the studies in the literature are examined, the effect of traffic-induced vibrations on bridges has been studied extensively (Domaneschi *et al.* 2017, Wieghaus *et al*. 2014, Xia *et al*. 2014). On the other hand, there are fewer studies examining the negative effects of traffic directly on the structure, considering human comfort threshold values.

This paper addresses the absence of criteria and guidelines in the Turkish Building Seismic Design Code 2018 (TBSDC-2018) and endeavors to raise awareness among building constructors regarding the significance of this issue. The current study investigates peak ground acceleration (PGA), peak ground velocity (PGV), peak ground displacement (PGD), and frequency content of ground motions induced by various traffic sources, aiming to scrutinize the adverse effects of these vibrations on structures by considering key parameters.

2. Investigation scope: Traffic characteristics and site vibration records in the study area

In the current research, the study area is designated as the Atakoy district, a prominent and longstanding residential block neighborhood situated on the western side of Istanbul, adjacent to the D-100 (or E-5) main road and the coastline of the Sea of Marmara (refer to Fig. 1). While the streets and avenues within the immediate vicinity experience relatively low vehicular traffic, the D-100 highway stands out as one of Istanbul's major thoroughfares. The westbound lane leads to the western borders of Turkey, while the opposite lane directs traffic toward the city center. This highway constitutes Istanbul's most heavily trafficked route, featuring six lanes, two-lane frontage roads on both sides, and a dedicated two-lane section for municipal buses between the westbound and eastbound lanes.

Adjacent to the highway, a subway line operates from early morning to midnight, facilitating high-capacity public transport trains every 6-10 minutes in both east-west and west-east directions. The Istanbul Metropolitan Municipality (IMM) continuously monitors and records traffic volume a

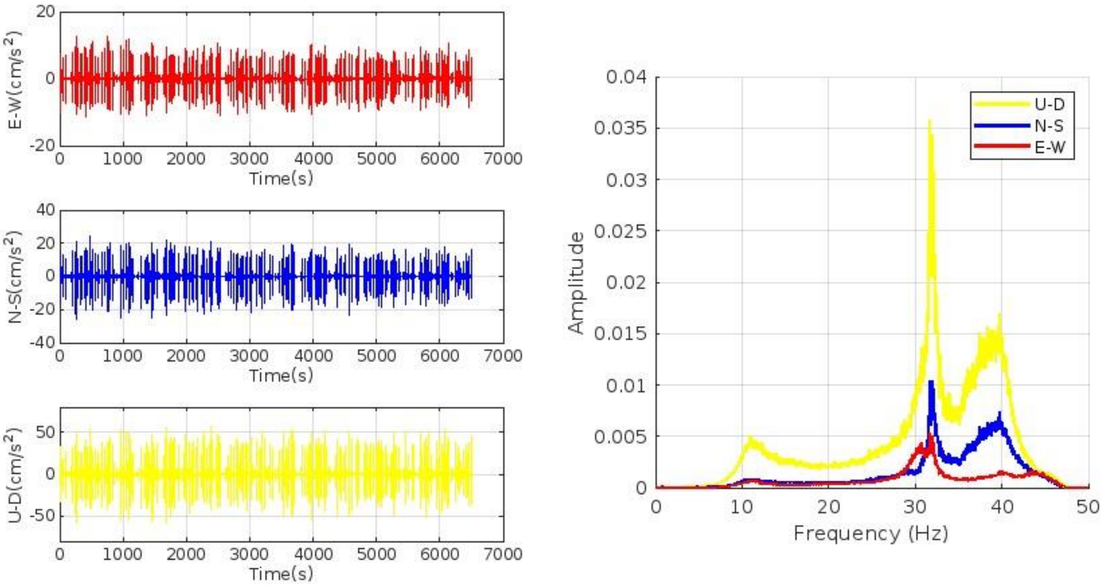
Fig. 1 An aerial photograph of the highway, red arrows show the location of the measurement stations A and B (inlet) The location of the Atakoy district

and average speed on the highway at 5-minute intervals. Utilizing IMM data, Dikmen *et al*. (2016a) have illustrated the number of vehicles per lane per hour and the average slowness (reciprocal of the average velocity) normalized to their peaks throughout a typical workday. Notably, their findings highlight a strong correlation between average speed on the highway and traffic volume.

In this study, for precise measurement and recording of traffic-induced vibration, an accelerometer device with 3-axis, ± 2 g full calibration, sensor noise level ≤5[µg⁄(Hz)^(1⁄2)] and sensitivity 2000[mV⁄g] features was used. This device has a 24-bit analog/digital converter and a large-capacity memory card. The data utilized in the present study consists of strong motion waveforms recorded at stations A and B. The records are visually depicted in Figs. 2 and 3. Initial data processing steps, including baseline correction and filtering, were applied to enhance the quality of the records. Subsequently, a detailed analysis was conducted to explore the frequency contents of the recordings and examine the acceleration-time history. For a comprehensive overview, the Peak Ground Acceleration (PGA) values corresponding to these records are tabulated in Table 1, providing a quantitative representation of the recorded ground motion intensities. This rigorous data analysis lays the groundwork for a nuanced understanding of the seismic characteristics in the study area, essential for the subsequent assessment of TIVs on the surrounding structures.

Table 1 PGA values of records in 3 directions

Station	E-W(cm/s^2)	N-S(cm/s^2)	U-D(cm/s^2)
A	12.696	25.845	58.972
B	2.889	2.705	10.947



(a) Acceleration-Time (b) Fourier Spectrum

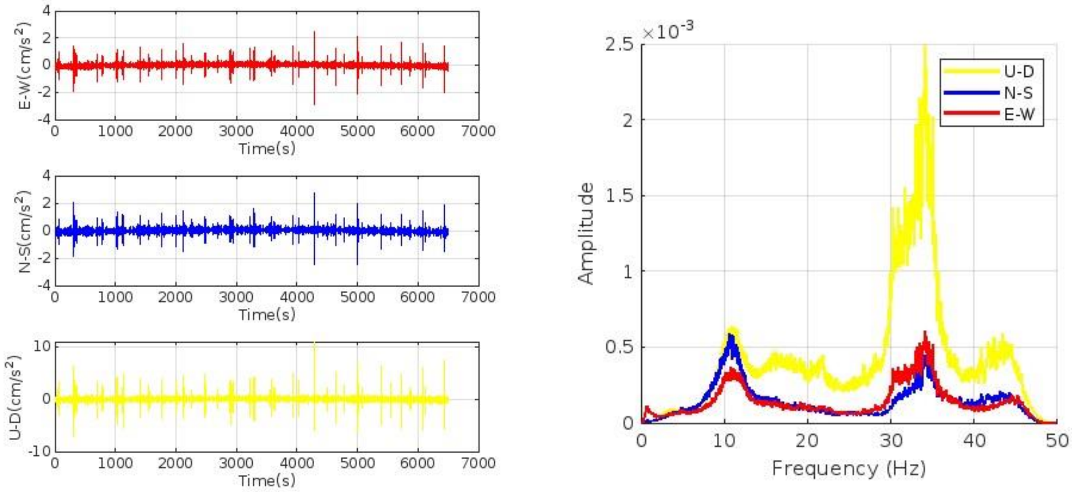
Fig. 2 Acceleration-time and Fourier spectrum of the recording at Station A

The examination of records from both stations, A and B, has focused on identifying the dominant regional frequencies. Notably, distinct dominant frequency values have been observed corresponding to different sources. Specifically, frequencies associated with TIVs exhibit dominance at 10 Hz.

For subway train-induced vibrations, the dominant frequency range is observed to be 35-45 Hz. In the case of bidirectional roadsides, specifically the middle region of the highway where only buses pass, dominant frequencies range from 30 to 35 Hz. This frequency analysis serves as a crucial foundation for understanding the varied sources contributing to the observed ground motion, facilitating a targeted assessment of their potential impact on the structures in the study area.

3. Description of analytical approach

In this analytical investigation, four building frames with varying numbers of stories 6, 10, 16, and 20 serve as the focal point. Uniformity is maintained across these frames in terms of load,



(a) Acceleration-Time (b) Fourier Spectrum

Fig. 3 Acceleration-time and Fourier spectrum of the recording at station B

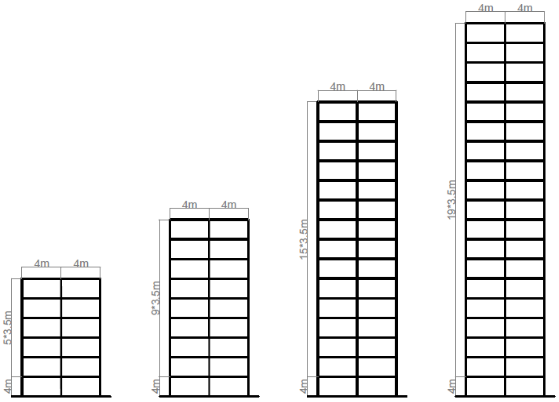


Fig. 4 Four 2-D frame models

geometry, and material properties. The structural models, conducted in a 2D frame system, are designed to scrutinize the impact of TIVs recorded at different distances. Crucial parameters within these models include a consistent ground level height of 4 m and subsequent upper floors at 3.5 m (Fig. 4). The material characteristics feature Young's modulus of 32 MPa for concrete and a unit density of 25 kN/m³ was considered. In addition, for both longitudinal and transverse reinforcement, S 420 (yield strength 420 MPa) steel bars which are hot rolled ribbed reinforcement are considered. The frames, characterized by two openings of 4 m width, comprise beams with dimensions of 25x35 cm, outer columns of 25x35 cm, and inner columns of 25x30 cm. Load considerations involve effective values of 3.5 kN/m² for dead load and 1.5 kN/m² for live load.

Table 2 Mode values of 4 frames with different story heights

Models	Mode 1(Hz)	Mode 2(Hz)	Mode 3(Hz)
6-story	2.145	6.59	11.6
10-story	1.30	3.96	6.95
16-story	0.78	2.40	4.32
20-story	0.60	1.87	3.44

The ensuing linear time history analysis ensures that the effects of TIV records are confined within the elastic region, allowing for a comprehensive exploration of structural responses across different building heights and configurations.

As a prerequisite for the linear time history analysis, firstly modal analysis is performed. The modal values of the four different frames are given in Table 2.

Considering the system behavior as linear, the obtained mode values and the frequency contents of the TIV's records would affect the response values of the models. In the below Equations, p_0 is the amplitude of load, and k is the rigidity of the system for the damped SDOF Systems. It is seen that the displacement of a harmonic movement can affect or a resonance state that may occur depending on the proportions of the natural angular frequency (ω_n) of the structure that has a function of the mass and stiffness of the structure itself and the angular frequency of excitation (ω) acting on the system (Chopra 2007). Eqs. (1) and (2) are used for the Damped SDOF system and are given below

$$f = \frac{\omega}{2\pi} \tag{1}$$

$$u_{max} = \frac{p_0}{k} * \frac{1}{\sqrt{\left[1-\left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\xi\frac{\omega}{\omega_n}\right]^2}} \tag{2}$$

The choice of the Ataköy region in Istanbul for the current study is motivated by the high traffic density in this area. TIVs resulting from both highway and subway traffic were systematically recorded at various distances. The impact of these vibrations on buildings is scrutinized, taking into account inherent uncertainties. Initially, the analysis focuses on examining the Peak Ground Acceleration (PGA) and frequency contents of the recorded vibrations. Subsequently, the investigation delves into the assessment of vibrations within buildings with varying numbers of stories. Key parameters such as peak acceleration, velocity, and displacement are considered, and their variations concerning different building stories are thoroughly examined. To represent the diverse building inventory of the region, two-dimensional frames with different periods are meticulously modeled.

Through the analysis of recorded data, the adverse effects of these vibrations on buildings are evaluated. The assessment is based on specific comfort limit values, particularly considering the maximum response velocity parameter. This comprehensive approach aims to shed light on the nuanced dynamics of TIVs and their potential implications for the structural integrity of buildings in the Atakoy region.

4. Analysis of the traffic-induced vibrations

4.1 Assessment of parametric study

The investigation delves into the parametric study of TIVs, focusing on the assessment of maximum horizontal displacement (MHD), maximum horizontal velocity (MHV), and maximum horizontal acceleration (MHA) values across four different-story frames. The analysis utilizes the E-W component of the records obtained from stations A and B in the field as input.

Fig. 5 illustrates the variation of MHD values across the four models about different story levels. The results indicate that the highest displacement values occur at the roof levels. Notably, the 20-story model exhibits the maximum displacement values when compared to other models. Additionally, a comparison between stations A and B reveals that MHD values obtained from station B are consistently higher.

Fig. 6 illustrates the variation in Maximum Horizontal Velocity (MHV) response values across different story frames. An observation reveals that MHV values for 6 and 10-story frame models occur predominantly on the 1st floor, while for 16 and 20-story models, these values manifest on the 8th and 18th floor, respectively. Notably, for station B, MHV values are concentrated in the upper stories, indicating distinctive patterns in the distribution of horizontal velocity across different building heights and locations.

Fig. 7 presents the Maximum Horizontal Acceleration (MHA) values for both stations A and B. Notably, for station B, MHA values consistently occur on the 1st floor across all models. Conversely, for station A, MHA is obtained on the 1st floor for 6 and 10-story models, and on the 2nd floor for 16 and 20-story models. It is worth mentioning that the MHA values for station A surpass those of station B, with the 20-story model exhibiting higher acceleration compared to other story models.

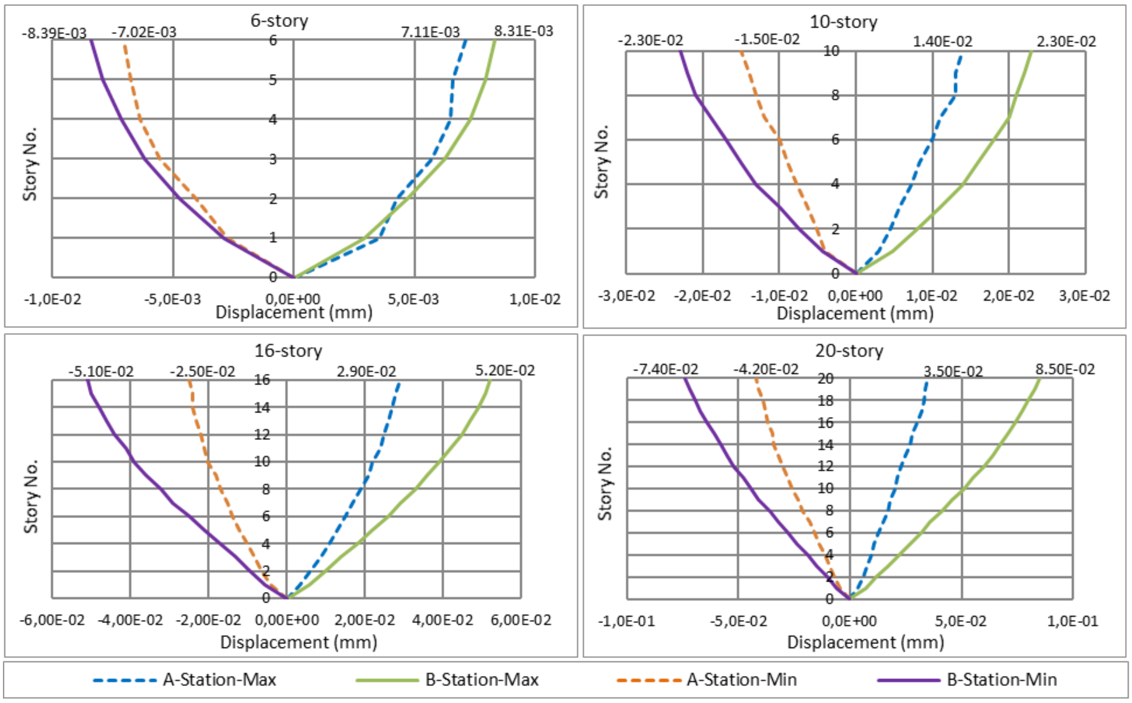


Fig. 5 Maximum horizontal displacement response values of E-W components of stations A and B

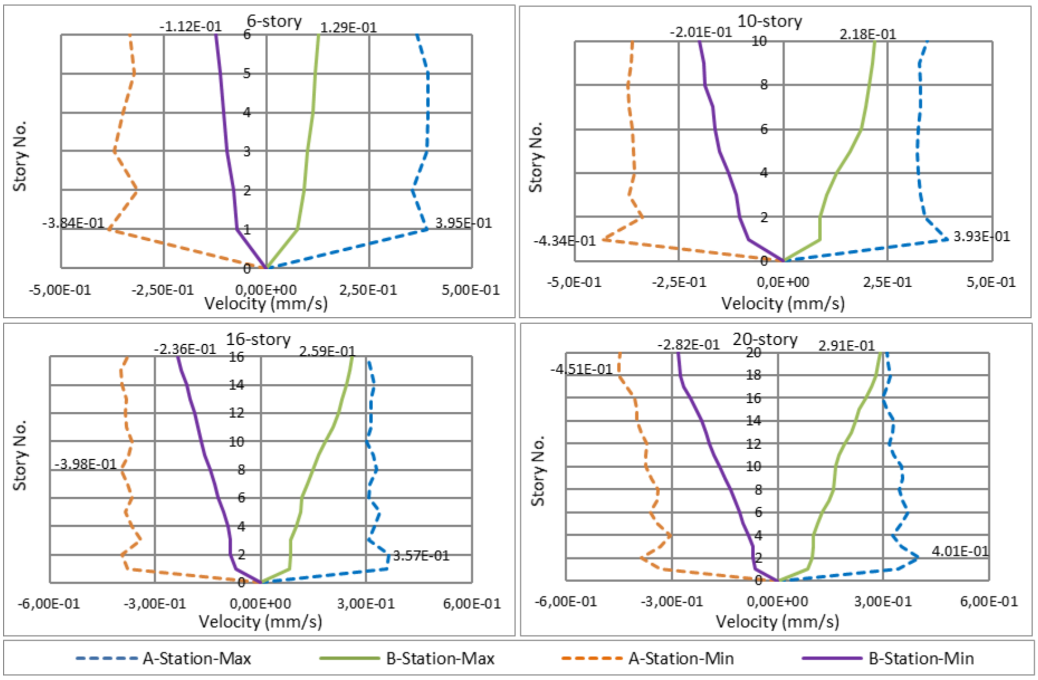


Fig. 6 Maximum horizontal velocity response values of the E-W components of the A and B stations

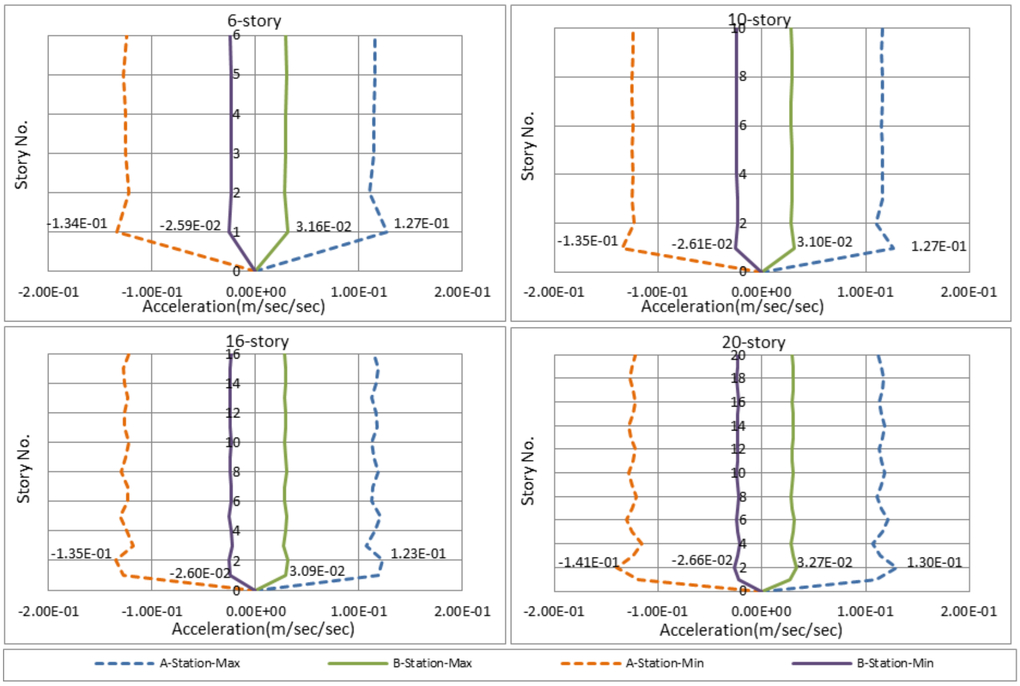


Fig. 7 Maximum horizontal acceleration response values of E-W components of A and B stations

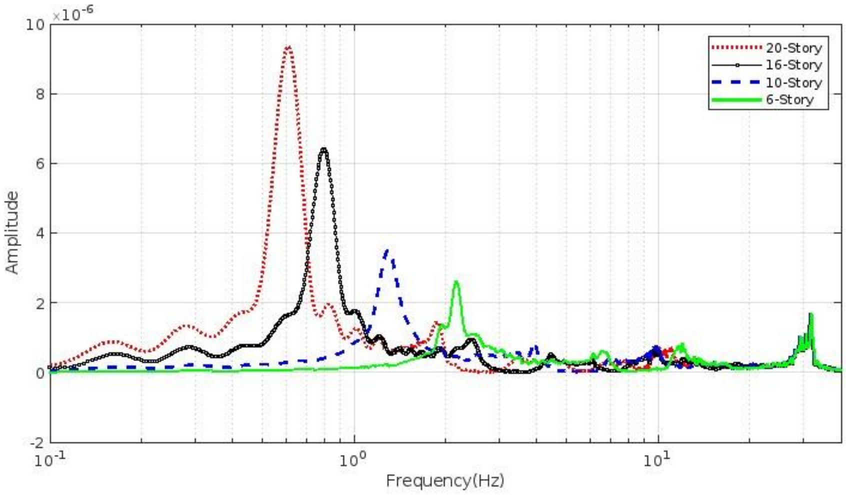


Fig. 8 Dominant frequency of Station A (E-W component)

4.2 Vibration levels and human comfort limits

An analytical approach has been employed to assess the response velocity values induced by TIVs in structures. The analysis considers the frequency contents on the rooftops of four selected models. Initially, the procedure encompasses all three components of records; however, for the sake of conciseness and due to the similarity of results, the East-West component (ASEWD) for station A has been chosen, and the outcomes are depicted in Fig. 8.

In Section 2, an analysis of the frequency contents of the acceleration recordings is conducted, revealing three distinct dominant regions corresponding to different vibration sources 10 Hz, 30-35 Hz, and 35-45 Hz, respectively. The first three modes of the four different models are provided in Table 2. Building on this information, the frequency contents of the response velocity-time history at the top story of the models are derived. Additionally, the response velocity-frequency graphs for the four models correlate with the dominant frequency values, each structure aligning with the frequency value of the first mode.

Fig. 8 demonstrates that the response values of the ASEWD record within the 20-50 Hz range exhibit consistent amplitudes across all four models, indicating a transition of the structure into vibration at low frequencies. The examination of energy distribution values in the power spectrum graph induced by TIVs reveals that the energy values at frequencies triggering structural vibration are notably lower compared to those at higher frequencies. Consequently, TIVs induce minimal response effects in the structure, suggesting a low potential for resonance hazards.

This study concludes that the likelihood of resonance hazards occurring in the structure due to TIVs is very low, emphasizing the overall low impact of TIVs on structural response.

The final section of this study delves into the comparison of the maximum response rates induced by TIVs at the floor levels of four different models. Velocity values are meticulously compared and examined against the specified limit values present in various national and international documents, including standards, codes, construction vibration criteria, guideline parameters, and defined limits relevant to TIV assessment.

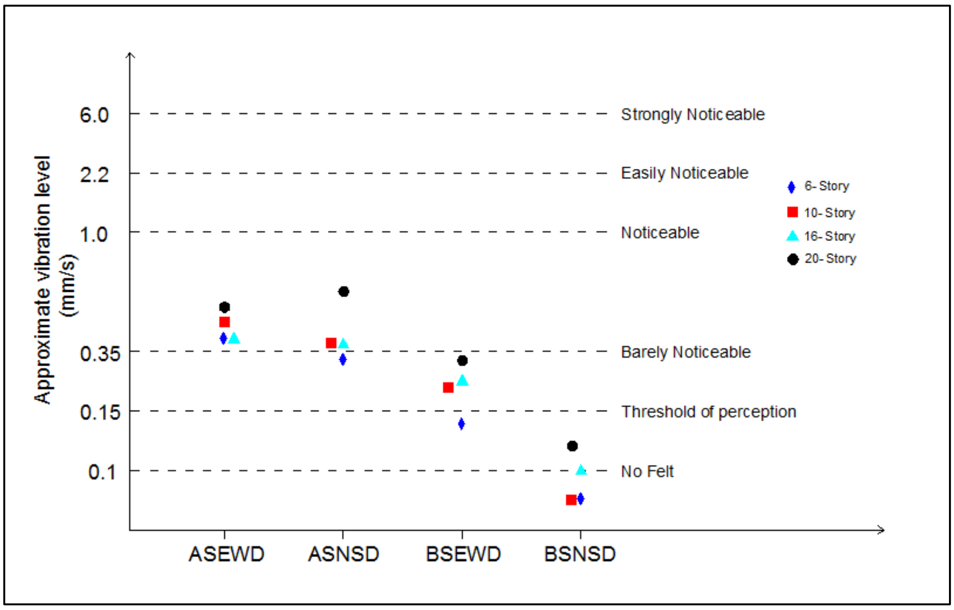


Fig. 9 TIV's assessment for typical human perception of approximate vibration levels

In Fig. 9, human comfort limits derived from the evaluation of multiple standards, norms, recommendations, and codes are presented. This figure provides an assessment of TIVs concerning the typical human perception of approximate vibration levels. For station A, recorded values from the four different story frames, considering both east-west (ASEWD) and north-south (ASNSD) components, have surpassed the limits defined for barely noticeable conditions. Conversely, for station B, recorded values in both components (BSEWD and BSNSD) remain below the barely noticeable limits. Furthermore, it is observed for station B that the recorded values for the north-south component of stories 6 and 10 fall below the "no felt" limit, indicating conditions where vibrations are imperceptible. This nuanced assessment aligns with the standards and guidelines specified in the literature, offering insights into the levels of human comfort and perception in the context of TIVs.

Upon scrutinizing standards relevant to TIVs, it becomes evident that parameters expressing the magnitude of vibrations in buildings exhibit significant variation. Moreover, differences in defining structural types play a pivotal role in establishing structural damage limits, as illustrated in Table 3. Consequently, certain limitations are imposed in these evaluations by accounting for the parameters in the structure and velocity assessment.

In this context, the Peak Particle Velocity (PPV) parameter is employed for vibration evaluation, specifically considering residential buildings as the structural type. By implementing this restriction, the summarized key points from the standards are presented in Table 3, outlining the structural damage limits based on the PPV parameter. This comprehensive approach acknowledges the diverse perspectives within existing standards and aims to provide a cohesive understanding of the limits associated with TIVs in the context of residential structures.

In the present study, the modeled frames represent residential buildings, aligning with the criteria stipulated in existing standards. Notably, the structural groups delineated in standards

Table 3 Structural damage limits for building vibration due to traffic effects

DIN4150-3				
	The foundation at a frequency of			Plane of floor of upper story
Frequency (Hz)	< 10 Hz	10-50 Hz	50-100 Hz	All frequencies
PPV	5 mm/s	5-15 mm/s	15-20 mm/s	15 mm/s
SN640 321a				
Range of frequency (Hz)				
Frequency (Hz)		10-30 Hz	30-60 Hz	
PPV		8 mm/s	8-12 mm/s	
BS7385-2 1993				
Range of frequency (Hz)				
Frequency (Hz)	4-15 Hz	15-40 Hz	40 Hz <	
PPV	50 mm/s	50 mm/s	50 mm/s	
	15-20 mm/s	20-50 mm/s	50 mm/s	

exhibit inherent differences. In scrutinizing the limit velocity values defined for different frequency ranges, it becomes evident that the DIN4150 standard demonstrates heightened sensitivity to TIVs in residential buildings, while the BS7385-2 standard adopts a more flexible approach.

The DIN 4150-3 standard categorizes Structures-1 as dwellings and buildings of similar design and/or occupancy. In the SN640 321a standard, Structure-2 is defined as buildings with foundation walls and floors in concrete. Conversely, the BS7385-2 standard introduces two distinct building groups: Structures-3, denoting reinforced or framed structures in industrial and heavy commercial buildings, and Structures-4, representing unreinforced or light-framed structures in residential or light commercial type buildings. Table 3 presents the results derived from the recorded field data, subsequently employed to evaluate the Peak Particle Velocity (PPV) parameter. Importantly, these results indicate no structural damage, affirming the resilience of the modeled residential buildings to the induced vibrations, as assessed against the specified standards.

5. Conclusions

In this in-depth analytical exploration, centered on the records of TIVs from the bustling Atakoy region in Istanbul, Turkey, a wealth of significant findings has emerged. The study meticulously reveals that the levels of TIVs experienced within the structures surpass established thresholds for human comfort, exerting a discernible negative impact on the well-being and work efficiency of occupants. Crucially, despite these elevated vibrational levels, the study firmly establishes that classical residential buildings remain resilient, devoid of any imminent structural damage risk. Beyond its technical revelations, this study aspires to be a catalyst for heightened awareness within the community regarding the profound influence of TIVs on buildings. It propels the argument for the inclusion of substantive discussions on TIVs within the building standards of Turkey. Recognizing the pivotal role of addressing TIV-related challenges in the swiftly evolving landscape of urban development in the country, the study emphasizes the need to weave considerations of these vibrations into the fabric of construction planning. Looking ahead, the study underscores the paramount importance of contemplating the potential detrimental effects that TIVs may exert on emerging structures. It advocates for a paradigm shift in future construction endeavors, urging a comprehensive understanding of TIVs' impact on both human comfort and structural integrity. In essence, this study emerges not merely as a technical investigation but as a beacon guiding informed decisions and considerations in the nuanced realm of contemporary building practices.

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