Journal of Vibration Engineering & Technologies
https://doi.org/10.1007/s42417-024-01513-x

ORIGINAL PAPER

Impact of Train-Induced Vibrations on Residents' Comfort and Structural Damages in Buildings

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Received: 30 March 2024 / Revised: 3 July 2024 / Accepted: 9 July 2024

Abstract

The rapid growth of urbanization and the progress of industrialization have resulted in the construction of over or near-track buildings. Train-induced ground-borne vibrations have attracted attention because they can damage buildings and cause residents discomfort. This study conducted a series of finite element analyses on three 5-story concrete framed buildings, which were subjected to the passage of trains at various speeds. One of the buildings was modeled as an over-track building, whereas the other two buildings were located in close proximity to the track but at different distances. The present study investigated the impact of train speed and track-to-building distance on the acceleration and velocity responses of buildings. The comparison of residents' comfort levels and the structural safety of buildings against potential damages was conducted using international standards as the controlling criteria. Furthermore, an efficient mitigation technique was implemented, involving the utilization of open trenches with different depths between buildings and the railway track. This approach was employed with the aim of minimizing the detrimental impacts caused by trains-induced vibrations. The findings indicated that the over-track building was impacted by the train-induced vibrations more than near-track buildings. Furthermore, it was shown that although the passage of high-speed trains can disturb the comfort of building residents and potentially cause some structural damage to buildings, it did not lead to any significant story drifts in the structures. Finally, the minimum required depth of open trenches to mitigate train-induced vibrations was computed for every type of buildings and train speeds.

Keywords Train-induced vibration · Open-trench · Residents' comfort · Structural damage · Over-track building · Finite element modeling

Introduction

High-speed trains are playing an increasingly significant role in making transportation faster and better connected in densely populated areas [1–3]. Due to train traffic, ground vibrations are generated that can negatively affect surrounding buildings, infrastructures, and residents [4, 5]. Train-induced vibrations tend to be more pronounced in over-track buildings due to their close distance to the passing trains. These buildings create efficient pathways for vibrations to travel, leading to direct transmission through the building and potentially causing amplification. During the last decades, various numerical and experimental studies have been conducted to examine the effect of train-induced vibrations on nearby and over-track buildings and residents [5–11].

Anderson [12] conducted vibration measurements in two buildings exposed to railway-induced vibrations at their foundations. He discovered that noticeable vibrations, with dominant frequencies ranging from 5 Hz to 50 Hz, could propagate through the ground to adjacent buildings.

Francois et al. [13] investigated the impact of dynamic coupling between soil and structure on nearby buildings. They demonstrated that assuming consistent movement between the building base and the incident wave field could lead to inaccurate vibration calculations.

Xia et al. [14] conducted experiments to explore the vibrations induced by railway trains on the surrounding ground and a nearby multi-story building. They measured velocity responses at various locations within the

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building. The findings indicated that velocity response levels on the building floors rise with increasing train speed and diminish with distance from the railway track. Freight trains, being heavier, produce more pronounced vibrations compared to lighter passenger trains. Within the multi-story building, lateral velocity levels escalate consistently with floor elevation, while vertical levels exhibit fluctuating patterns. Notably, indoor floor vibrations register significantly lower magnitudes than outdoor ground vibrations.

Sanayei et al. [15] conducted measurements of surface train and subway-induced vibrations within six buildings built on foundation slabs. Their findings revealed that the measured vertical velocity levels exceeded the horizontal vibration components within these buildings. Based on their results, they concluded that vertical vibrations are likely more significant in the design of mitigation strategies aimed at reducing the transmission of vibrations to upper floors. Sanayei et al. [16] introduced the impedance model, which ignored the coupling loss between the soil and the building structure and used the vibration at the bottom of the structure as the model input.

Coulier et al. [17] demonstrated that when the distance between the vibration source and the building is less than the wavelength in the soil, the coupling effect between the soil and the building's shallow foundation becomes highly significant. Hesami et al. [18] investigated the impact of train-induced vibrations in an urban area near a railway in Iran and recommended an optimal distance of 18 m from the track for constructing buildings.

Zou et al. [19] conducted field measurements of vibration during subway operations in Shenzhen, China, to characterize the vibration transmission in the metro depot and over-track buildings. They compared the train-induced vibrations with the restrictions set forth by the Federal Transit Administration (FTA) criteria. They showed that the vertical vibration energy is directly transmitted through the columns on both sides of the track into the floors, amplifying vibration on the platform by up to 6 dB greater than ground levels at the testing line area. They advised that in order to prevent severe vertical vibrations, new over-track buildings within 40 m on the platform over the rails throat areas should be carefully designed.

Ribes-Llario et al. [20] studied the transmission of train-induced vibrations to buildings located in the vicinity of the track. They demonstrated that the vertical vibrations in the foundation slab are highest at the corners, while horizontal vibrations remain constant along the edges. Additionally, the vibrations consistently increase as they propagate upwards through the building. Kuo et al. [21] analyzed the dynamic interaction between soil and structure by examining coupling loss, which they defined as the difference in vibration levels between the interior and exterior of a building.

Tao et al. [22] presented an analysis of train-induced vibration and noise levels within over-track buildings at a metro depot. The measured levels were compared with both Chinese and US FTA standards to assess their potential impact on building occupants in terms of annoyance, considering both feelable vertical floor vibration and radiated noise. Vibration levels at the ground columns supporting the low-rise building, affected by passing trains in the throat area, significantly exceed levels observed at the ground adjacent to load-bearing wall support structures of the high-rise building, especially for high-speed trains. However, levels adjacent to the building columns within the low-rise building are only slightly higher than those observed at floors within the high-rise building.

Qiu et al. [23] assessed the vibrations in a building caused by a train running on a concrete floor slab to measure the impact of train operations on building floors. They analyzed the transmission of these vibrations from the concrete ground to the building floor. Hu et al. [24] unified the train, track structure, and building structure, proposing a model for predicting vertical vibrations caused by trains passing over building floors.

In light of the demonstrated adverse impacts of train-induced vibrations on both buildings and residents in the literature, mitigation of these vibrations has become a popular concern for engineers. Research on train-induced vibrations of soils and relevant isolation methods can be classified into three categories. The first category is active isolation, which aims to reduce vibrations at the source. This includes optimizing the vehicle model, train speed, and track system [25]. An example of active isolation is an active vibration control system, which uses sensors and actuators to detect and counteract vibrations in real-time. These systems often employ feedback loops and electronic control units to apply forces that cancel out incoming vibrations, effectively isolating sensitive equipment or structures from unwanted disturbances [26].

The second method is identified as passive isolation, which focuses on protecting the target building against external disturbances. It was shown that using the floating slab track can significantly reduce the vibrations of a railway concrete slab track [27–31]. Stichel et al. [32] showed that active suspension is an impressive technology that can improve the train dynamic performance and reduce the acceleration induced by train passage.

Talbot and Hunt [33] and Wu et al. [34] proposed efficient computational approaches to analyze the effect of pile foundation-soil interaction under train loads. The isolation effect of different foundations, i.e., retaining walls, pile foundations, slabs, strip and box foundations, and soil improvements around the building has been investigated [13, 35]. It has been shown that the soil densification around the building is an efficient way to reduce the train-induced vibration of buildings. Coelho and Koopman [36] suggested that by intervening at the foundation layout and changing the structural scheme of buildings through changing the alignment of the foundation beams, a reduction in the vibration can be achieved.

The third and most popular train-induced vibration mitigation technique is locating the wave barriers in the propagation path to reflect incident waves. These wave barriers can be sheet-pile walls [37, 38], rows of solid or hollow concrete or steel piles [39–44], open and in-filled trenches [25, 45–55], and wave impeding blocks (WIBs) [56, 57]. A comprehensive study introduced and reviewed the railway vibrations and the available strategies to tackle the effect of this vibration on nearby buildings [58].

Although the active and passive isolation techniques exhibit valuable vibration attenuation performance, they have some inherent limitations as below:

- Active methods, which rely on complex control systems and actuators, can be costly to install and maintain. In addition, this method, such as vibration-absorbing materials, can be limited by their effectiveness within specific frequency ranges and may face challenges related to resonance and degradation over time. These techniques can also require temporary interruptions in train operations during implementation.
- Employing various techniques such as retaining walls, pile foundations, slabs, strip and box foundations, and soil improvements around buildings to mitigate train-induced vibrations also have their set of limitations. Most of them demand ongoing maintenance and in case of existing buildings, they are impractical. For over-track buildings, the aforementioned methods can be more complex and impose high cost.
- Most of the studies in the literature have focused on the effect of train-induced vibration on only nearby or over-track buildings. If a mitigation method has been employed for a nearby building, its efficiency should be assessed to the over-track building as well and vice versa.
- While most of the studies in the literature have demonstrated the effectiveness of mitigation techniques in reducing train-induced building vibrations, they have not adequately assessed whether these methods are sufficient to ensure the comfort of the building's residents or prevent the structural damage.

While track and rail irregularities significantly impact train-induced vibrations, these factors have been largely neglected in previous studies. Similarly, the properties of the fastening system, which also influence train-induced vibrations, have not received adequate attention in the literature. As a result, the findings from earlier research may not accurately reflect reality. These limitations prompted the author to conduct a numerical study that simultaneously considers nearby and over-track buildings. The novelty of the present study lies in the development of a comprehensive numerical model to assess the impact of train-induced vibrations on over-track and nearby buildings, focusing on residents' comfort and structural damage. Unlike previous research, this study examines the effects of train-induced vibrations on buildings situated at varying distances from the rail-track system, considering rail irregularities and fastening systems. It evaluates various aspects of structural and environmental impacts and compares the results against different international standards.

A finite element numerical model of soil-track system was constructed and validated with a model available in the literature, firstly. In the next step, a series of 3D finite element models were developed for three 5-story concrete framed structures (two of which as track nearby and one as over-track building) using PLAXIS3D. Parametric studies were conducted to evaluate the effect of the train speed and the distance of the buildings from the rail tracks.

The present study utilized a widely adopted, economically viable, and practical technique for mitigation. This technique involves creating open trenches between the railway tracks and buildings. The study focused on evaluating the effectiveness of open trenches stabilized with steel sheet walls in minimizing the impact of vibrations caused by passing trains on structures. Previous studies have evaluated the effect of open trenches as a vibration mitigation technique for reducing train-induced vibrations in buildings, but typically only in terms of either residents' comfort or structural damage prevention. Few studies have compared their results against the thresholds of a single standard and provided recommendations for the required depth and width of the trench. A gap exists here: the recommended depth/width ratio of an open trench in previous studies may satisfy one aspect but not meet the criteria for another. This study addresses this gap by evaluating the effect of train-induced vibration mitigation techniques on both environmental and structural aspects, comparing the results with multiple standards. The final decision in this study is based on multi-criteria analysis and various standards, providing more comprehensive and practical information for engineering applications.

Methodology

Description of the Finite Element Model

In this study, a finite element commercial software (PLAXIS3D) is used in the analysis to model the subgrade soil-railway track system. A three-dimensional finite element analysis for a rail track system subjected to moving train loads was constructed and validated by a model presented in the literature [59]. So, all the input parameters and train loads were selected from the reference study. The analysis included static and dynamic phases. In the static phase, the boundary conditions and stability of the soil-track model were controlled in the absence of moving train load. In the dynamic analysis, the effect of the inertia forces of the soil mass on the moving train loads-subgrade soil interactions was considered. The dynamic equilibrium equation is given in Eq. (1) [60]:

$$M\ddot{u} + C\dot{u} + Ku = F \tag{1}$$

where, [M] is the mass matrix, [C] is the damping matrix, [K] is the stiffness matrix, [u], [$\dot{u}$] and [$\ddot{u}$] represent the displacement, velocity, and acceleration matrices respectively. [F] is the load.

The damping matrix [C] can be calculated from Eq. (2) [61]:

$$C = \alpha M + \beta K \tag{2}$$

α and β are Rayleigh damping factors which were considered as 0.2454 and 0.0016, respectively [59]. The initial time step used in the analysis was 0.01 s.

The subgrade soil model considered in this study had plan dimensions of 180 m × 100 m with 30 m depth (see Fig. 1). The standard boundary conditions for the static analysis have been employed similar to many previous studies in the literature [62, 63]. The lateral boundaries of the model were allowed to move only in vertical direction and fixed in horizontal directions. The bottom boundary was fixed to prevent any movement. Absorbent boundaries [64] also were added to the model's lateral sides and bottom to remove inaccurate results caused by wave reflection in the dynamic analysis. The absorbent boundaries are governed by Eqs. (3) and (4):

$$\sigma_n = -C_1 V_p p \dot{u}_x \tag{3}$$

$$\tau = -C_2 V_s p \dot{u}_y \tag{4}$$

where, σ_n and τ are the normal and shear stresses, respectively. C_1 and C_2 are relaxation coefficient and were set equal to 1 (according to PLAXIS3D manual). $\dot{u}_x$, $\dot{u}_y$, V_p, and V_s are horizontal velocity, vertical velocity, pressure wave velocity, and shear wave velocity, respectively.

For modeling of the subgrade soil and rail track system, 10-nodded solid elements were used. In the constructed model, number of the generated elements and nodes were 21,960 and 41,739, respectively. The mesh size was set to fine. The train loads were simulated as the moving point loads option available in PLAXIS3D which allow a more straightforward simulation of problems including traffic-induced loading. It is worth noting that modeling moving train loads as moving point loads is a common practice in the numerical modeling of trains on railways [18, 20, 59, 65]. Details of the model for subgrade soil and railway track system is shown in Fig. 1.

Constitutive Models used in the Numerical Analysis

Although some studies in the literature have used bi-linear elastic-plastic material with the Mohr-Coulomb failure criteria to simulate the subgrade soil for the case of a moving train, it was shown that using elastic perfectly plastic model

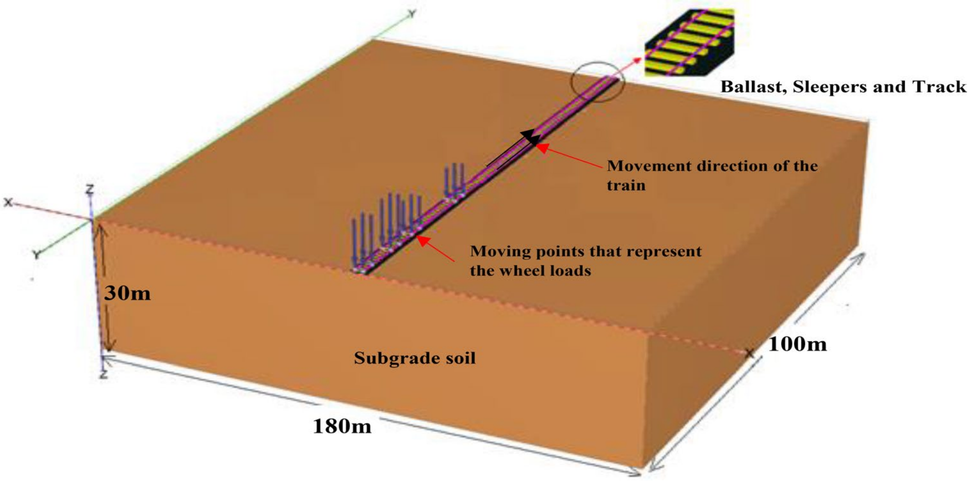

Fig. 1 Details of the model for subgrade soil-railway track system

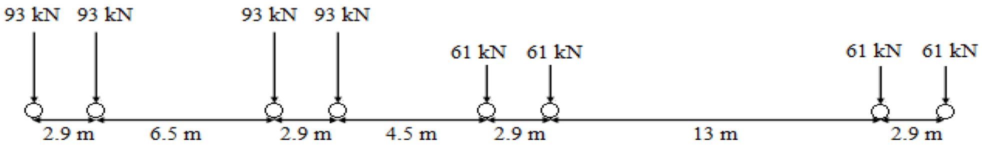

Fig. 2 Loading configuration of the moving train (obtained from [59])

Table 1 Parameters of the subgrade soil, ballast and sleepers (according to [59])

Material	γ (kN/m^3)	Young ModulusE (MPa)	Poisson Ratio, ν	Cohesion (kPa)	Friction Angle φ (°)	Damping Coefficients	
						α (s^{-1})	β
Subgrade	18.5	16	0.25	--	--	0.2454	0.0016
Ballast	17	134	0.3	20	48	2.38	0.001
Sleepers	23.5	25,500	0.2	--	--	0.39	0.00016

Table 2 Properties of the rail track (according to [59])

γ (kN/m^3)	E (MPa)	Area	I_2	I_3
78.5	206,000	7.67×10^{-3}	0.03038×10^{-3}	0.03038×10^{-3}

for the subgrade soil does not increase the accuracy of the analysis [59]. Furthermore, using the linear elastic model for subgrade soil in the case of moving train loads is common in the literature [59, 61, 66]. Hence, in this study, the subgrade soil, ballast, sleepers, and rail track were simulated using linear elastic model to avoid surplus iterations in the numerical analysis. Figure 2 presents the loading configuration of the moving train in the numerical model. Tables 1 and 2 tabulate the properties of materials used in the numerical model.

Validation of the Numerical Model

Once the 3D model of subgrade soil- rail track system was constructed and the input parameters were assigned to the elements, the train load and its passage was modeled by a series of moving point loads representing the wheels of the train as shown in Fig. 2. To validate the model, three dynamic analyses were performed and the soil-rail track systems were subjected to the passage of trains with different travel velocities: 100, 200, and 300 km/h. The measuring point for comparing with the reference study was located in the mid-span of the rail track. Figure 3 demonstrates the comparison of train-induced vertical settlements of the rail track. According to this figure, the vertical settlement of the rail track slightly increased by increasing the travel speed. Since there are good agreements between the results of the validation model with those presented in the reference study, it was concluded that the model has been constructed properly.

Modifying the Numerical Model to Address gaps in the Reference Study

It should be noted that the results obtained by Hadi et al. [59] are far from the reality since the track and rail irregularities as well as the rail fastening system have not been included. According to the literature, irregularities and rail fastening system are key factors to the affection of vibration characteristics of a track and greatly influence ground vibrations [67, 68]. Ignoring these details can result in the ineffective evaluation of vibration mitigation and noise reduction strategies, leading to suboptimal design solutions. Consequently, dynamic excitation due to a train running on track with irregularities and fastening systems is essential to the evaluation of train-induced vibrations in the ground or near-track buildings. To enhance the reliability of this study, fastening systems along the railroad and an irregularity in the mid-10 m section of the rail track were introduced in the numerical model shown in Fig. 1, followed by another analysis. In this due, the abrupt irregularity in the mid-10 m

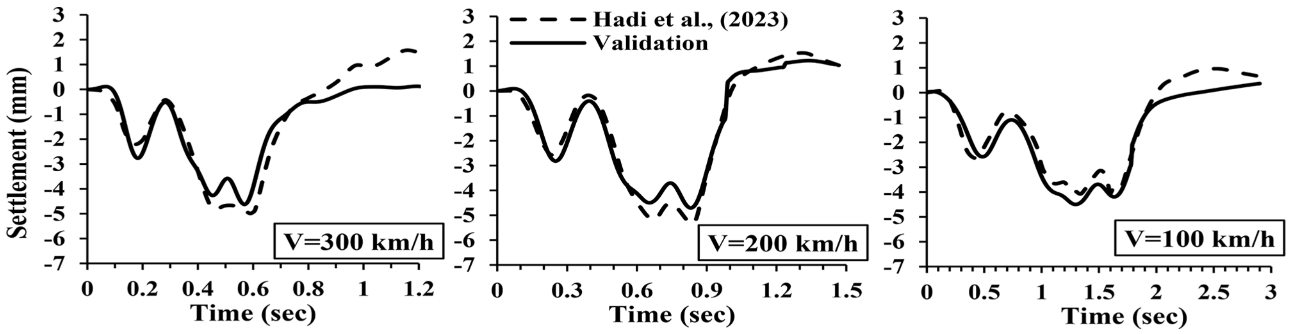

Fig. 3 Comparison of the vertical displacement of the railway track

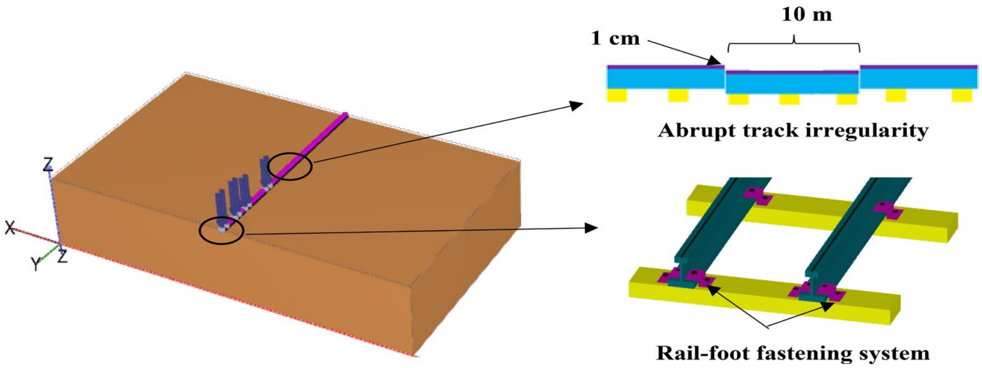

Fig. 4 Geometrical details of the track irregularity and the fastening system

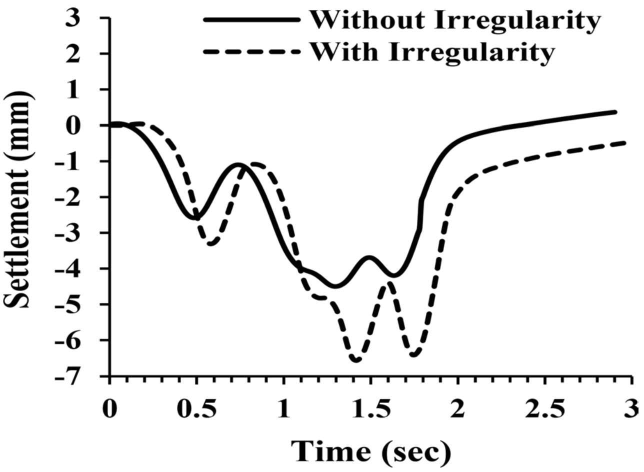

Fig. 5 Comparison of the vertical settlement of the track under the passage of a train in models with and without fastening systems and irregularity

section of the rail-track was modeled by intentional reduction of the height of this section by 1 cm compared to other parts of the track. Furthermore, the rail-foot fastening elements were modeled using the plate element with 1 cm thickness ($E=206$ GPa, $\gamma=78.5$ kN/m^3) and added to the model. Geometrical details of the irregularity and the fastening system are shown in Fig. 4. Figure 5 compares the vertical settlement of the track under the passage of a train traveling at 100 km/h in models with and without fastening systems and irregularity. This comparison clearly demonstrates the importance of including fastening systems and irregularities in numerical models. Consequently, the reference model in Fig. 1 was updated, and the model incorporating both train-track irregularities and fastening systems will be used hereafter.

Introduction of Over-track and Near-track Concrete Frame Buildings

As mentioned before, three 5-story concrete frame buildings were modeled in this study, one of which is an over-track and two others are near-track buildings with different distances from the railway. To investigate the effect of distance on the train-induced vibration in the buildings, two of buildings were located in distances equal to 6.5 and 12 m from the railway. The structural system of the floors are flat plates elements with 20 cm thickness. To simulate the beams and columns, a beam element was used in PLAXIS3D. The columns have a cross-section of 50 cm × 50 cm in the first floor and 45 cm × 45 cm in top floors. The beams have a cross-section of 40 cm × 40 cm. The columns have single concrete foundations of 1 m × 1 m with a thickness of 80 cm. Structural elements were modeled using linear elastic material with Young Modulus of $E=21$ GPa and the unit weight of $\gamma=25$ kN/m^3 that is for concrete. All the dimensions, structural details, rail-track irregularity zone, and arrangements of measuring points of the buildings were shown in Fig. 6. As shown in this figure, an interface element was considered between the soil and the foundation of buildings to simulate the interaction between these materials. It models frictional and adhesive properties, allows for relative movement and separation between contacting parts during dynamic analysis. The measuring points shown on the floors of the buildings are the locations where the results of the dynamic analyses were obtained and plotted. It should be noted that the different arrangement of measuring point on the buildings may affect the monitoring results. Further attempts are needed to evaluate this issue, which can be addressed in future studies.

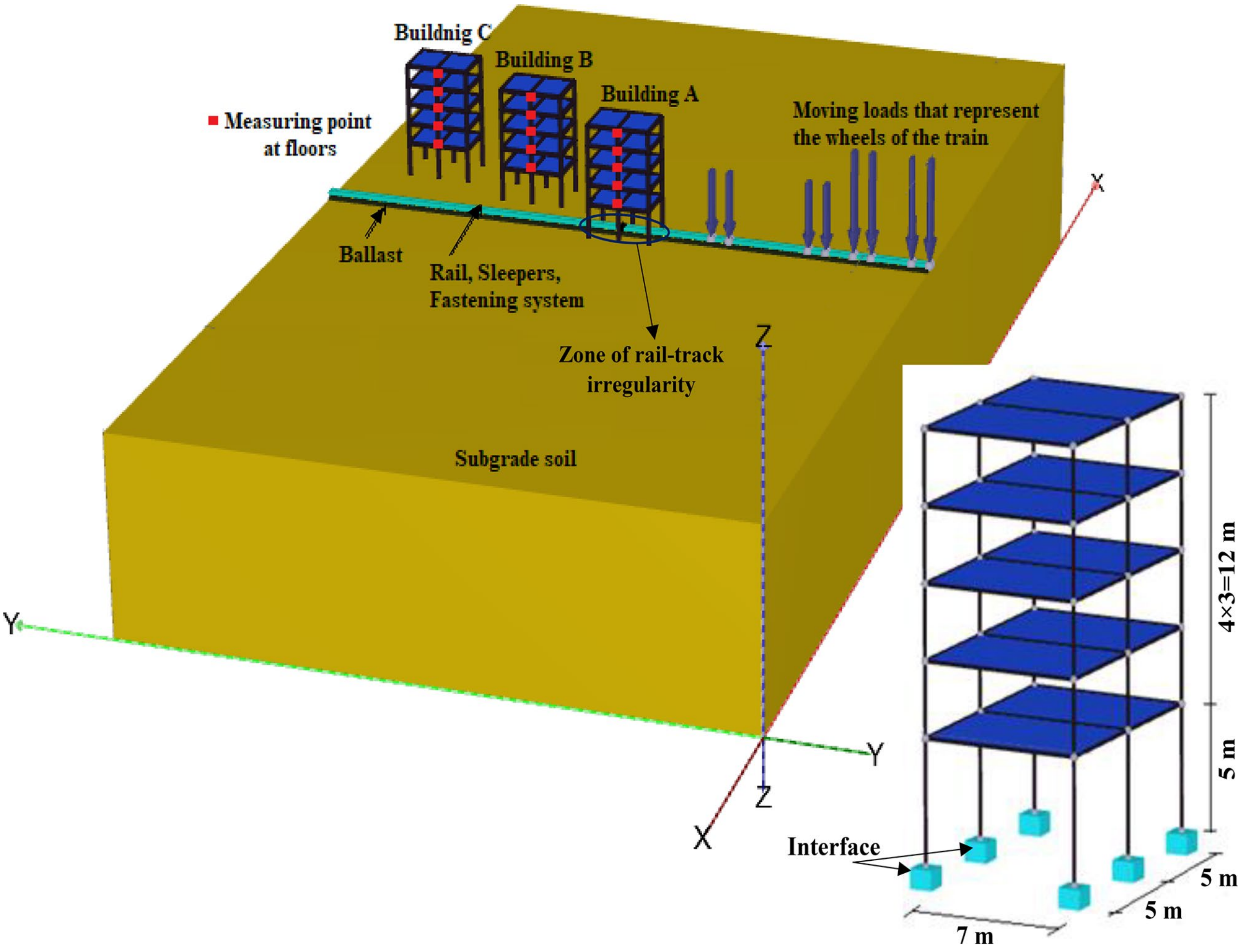

Fig. 6 Structural details and measuring points to get the dynamic responses in buildings

Numerical Analysis Results

Comparison of Vibration Components

In this paper, the effect of the distance between train tracks and the building edge was studied. As explained before, two possible locations for buildings was considered: over-track and near-track.

The vibrations levels transmitted to the soil and the buildings are assessed through the three components of acceleration: a_x, a_y, (horizontal acceleration components) and a_z (vertical acceleration components) of different measuring points at the selected locations of the buildings as shown in Fig. 6. After completion of dynamic analysis for three different train velocities, acceleration time histories for buildings were obtained. To maintain paper conciseness, only the results obtained for the first floor of the buildings were presented in Fig. 7, as a representative instance.

It is inferred from Fig. 7 that the train-induced acceleration in the buildings increases by increasing the train speed. For example, the vertical acceleration in an over-track building subjected to the passage of a train traveling at 300 km/h is 8.56 times greater than that at 100 km/h. Furthermore, the over-track building experienced higher accelerations due to its proximity to the railway tracks, compared to the near-track buildings. For example, when the train speed is 200 km/h, a_z on the first floor of building A is 87% and 135% greater than a_z in buildings B and C, respectively. The vertical acceleration in buildings subjected to train-induced vibrations is the dominant component due to the direct effects of vertical wheel-rail interaction and ground-borne vibrations, as shown in Fig. 7.

Influence of Train-induced Vibration on Buildings Residents' Comfort

As mentioned earlier, the vibrations caused by passing trains can have a considerable impact on buildings, particularly those are over-tracks. The well-being and comfort of the individuals residing in these buildings are of paramount

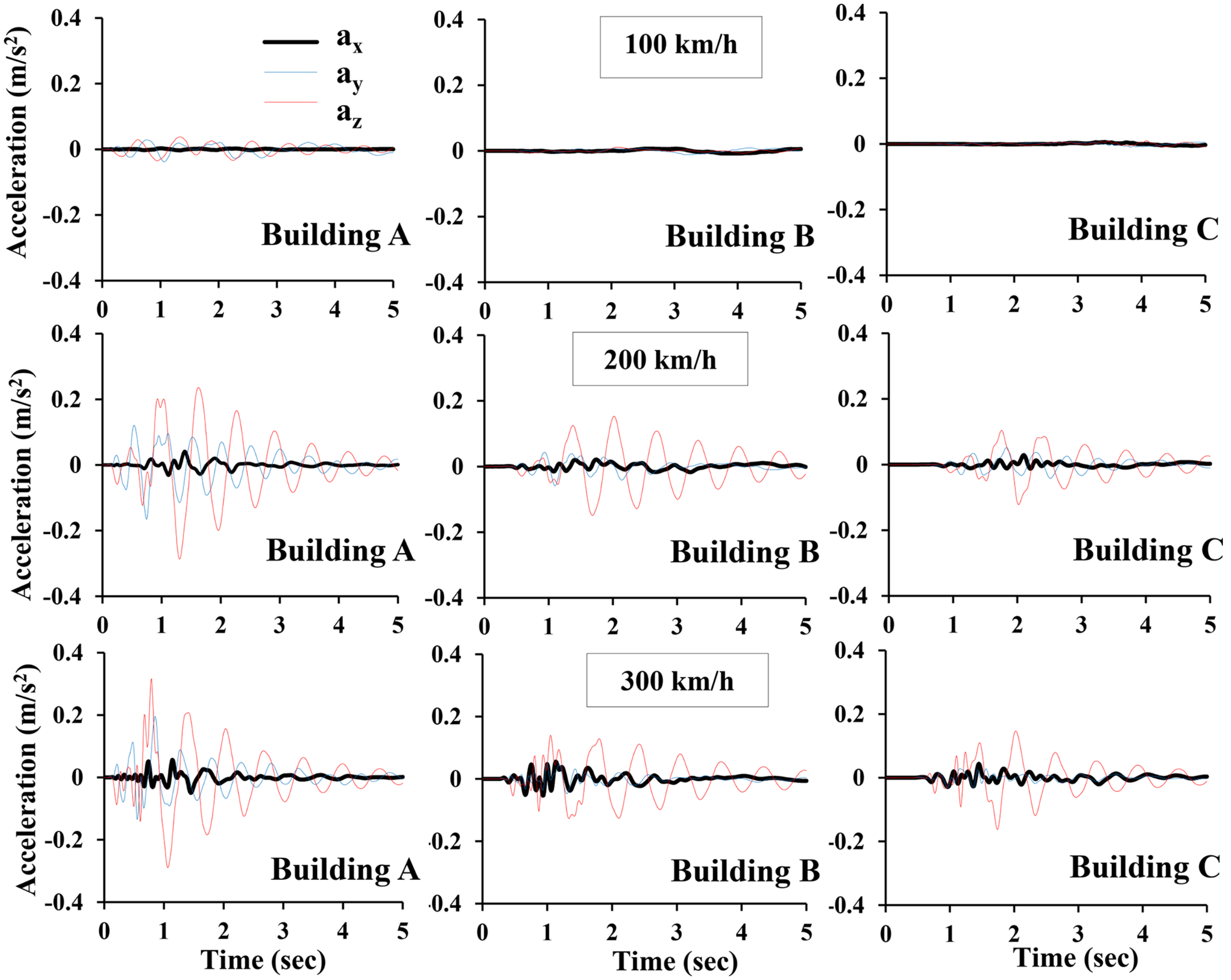

Fig. 7 Comparison of acceleration results in buildings subjected to train passages

importance since high speed trains can induce vibrations which significantly disrupt residents' daily life. While numerous studies have investigated the train-induced vibrations in buildings and explored various techniques to mitigate these vibrations [58], most of them have not adequately addressed the influence of vibrations on residents' comfort and the efficiency of mitigation techniques in achieving the desired comfort levels. One of the novel aspects of this study is the investigation of how train-induced vibrations affect residents' comfort in both over-track and near-track buildings at various train velocities, taking into account irregularities in the rail-track system. ISO2631-1 [69] has reported likely discomfort reactions to vibration environments, as defined by ranges of resultant total acceleration values, a_v. According to this standard, the total acceleration of vibration higher than 0.315 m/s^2 is considered as uncomfortable for people seating on floors. In the present study, acceleration measurements occurred on the measurement points shown in Fig. 6. The root-mean-square (rms) acceleration was calculated for each axis, and the corresponding weighting curve was applied [69]. The weighting process was calculated using Eq. (5):

$$a_w = \sqrt{\frac{1}{T}\sum {}_0^T a_w^2\left(t\right)} \tag{5}$$

where, $a_w(t)$ presents the weighted acceleration as a function of time in m/s^2, and T is the duration of measurement in seconds.

The resultant total acceleration of vibration in each floor was calculated by Eq. (6) as follow:

$$a_v = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2} \tag{6}$$

where a_{wx}, a_{wy}, and a_{wz} are the weighted rms acceleration in x, y, and z directions and k_x, k_y, and k_z are the multiplying factors, depending on the measurement points. ISO 2631-1 has suggested k values as follows: $k_x = k_y = k_z = 1$. Since the total duration of the dynamic analyses in this study was 5 s, T was given as 5 in Eq. (5). After performing dynamic analyses, a_v values at various measurement points were computed and displayed in Fig. 8. Based on the data in this figure, when a train travels at a speed of $V = 100$ km/h, the total vibration acceleration in all three buildings remains below 0.315 m/s², which is the comfort threshold for residents. Consequently, the passage of a train at this speed did not result in discomfort to residents in either over-track or near-track buildings. No vibration mitigation technique is required here. Upon increasing the train's speed to 200–300 km/h, it became evident that the total vibration acceleration in all the three buildings exceeded the threshold of 0.315 m/s² and residents reported discomfort. It is also demonstrated in Fig. 8 that by increasing the travel speed of the trains, higher a_v was recorded in buildings. Moreover, residents in the over-track building felt a higher level of discomfort. Therefore, a vibration mitigation technique will be required to eliminate this discomfort.

Investigation of the Effect of Train-Induced Vibrations on Story Drift Ratios of Buildings

In this section, the performance level of the buildings under study was evaluated after being subjected to train-induced vibrations. To this end, the story drift ratios of the floors for each building were calculated using Eq. (7) and compared to the limit stated by FEMA273 [70].

$$Story\ drift\ ratio = \frac{x_{i+1} - x_i}{H} \tag{7}$$

where H is the story height (i.e., 5 m for the first floors of the buildings and 3 m for the rest). x_{i+1} and x_i are the horizontal displacements of the center of mass at levels $i+1$ and i, respectively. According to FEMA273, a maximum story drift of less than 1.5% is classified as a life-safe performance level.

Figure 9 illustrates the maximum story drift ratios for each floor of the buildings. It is inferred from the figures that the story drift ratios in over-track building is higher than that in near-track buildings. Furthermore, the drift ratio on the first floor is higher than on the other floors because it typically experiences the highest shear forces and displacement due to direct interaction with ground vibrations. Additionally, the first floor absorbs most of the energy from these vibrations, leading to larger deformations compared to higher floors. The other floors exhibit similar drift ratios because the energy from the train-induced vibrations dissipates as it moves upward through the building, resulting in more uniform displacement and deformation.

It was concluded that the maximum drift ratios for all the buildings subjected to train-induced vibrations are far less than the 1.5% limit stated in FEMA273. Hence, the performance level of the buildings was not considerably affected by the train-induced vibrations.

Investigation of the Effect of Train-Induced Vibrations on Structural Damages in Buildings

The development of high-speed train networks in densely populated urban areas can have substantial impacts for the structural integrity of adjacent buildings. Through the years, there has been a significant rise in concerns regarding the potential for irreversible damages to structures located in close proximity to railway tracks. Investigating the impact of train-induced vibrations on the structural integrity of buildings is of paramount importance. These vibrations, generated by the passage of trains, have the potential to

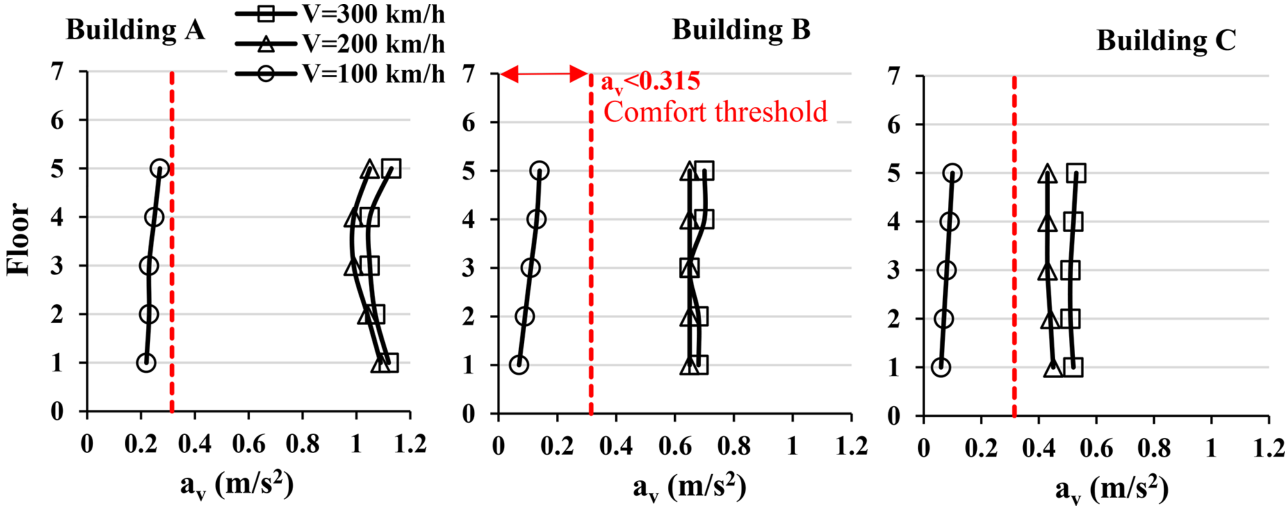

Fig. 8 The total vibration accelerations caused by passing trains at various speeds in different buildings

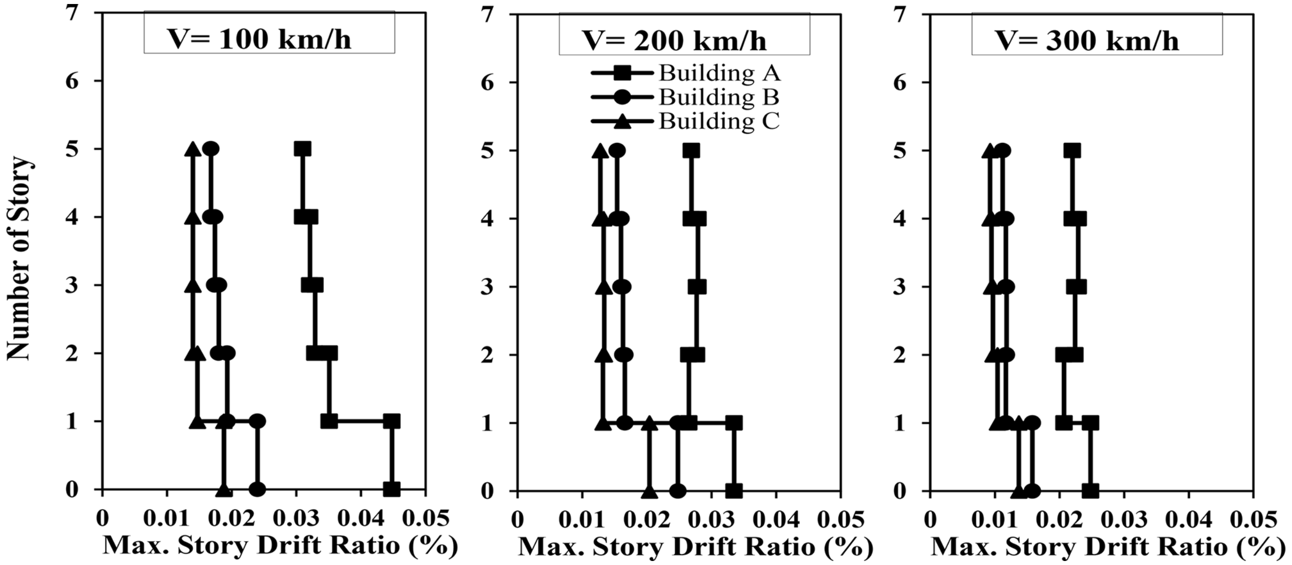

Fig. 9 Comparison of maximum story drift ratios in buildings subjected to different train velocities

compromise the safety and longevity of nearby structures. Understanding their effects allows to implement proactive measures to safeguard buildings and ensure the well-being of occupants.

Primarily, it is important to understand which parameter is the best descriptor to investigate the train-induced vibrations in the buildings. During the last decades, some researchers have shown that the peak particle velocity (*PPV*) is the best criteria to investigate the influence of ground vibrations on the structural damages in buildings [71–74].

There are generally four different approaches for *PPV* determination in the literature as follows [75]:

1. Maximum Resultant of Velocity Components [76–78]: it is calculated by Eq. (8):

$$PPV = Max\sqrt{(V_R)^2 + (V_V)^2 + (V_T)^2} \tag{8}$$

where, V_R, V_V, and V_T are radial (or longitudinal), vertical, and tangential (or transverse) velocity components, respectively.

2. Resultant of Maximum Velocity Components [79, 80]: it is calculated by Eq. (9):

$$PPV = \sqrt{(V_{Rmax})^2 + (V_{Vmax})^2 + (V_{Tmax})^2} \tag{9}$$

where, V_{Rmax}, V_{Vmax}, and V_{Tmax} are the maximum recorded values of velocity components.

3. Peak Unidirectional Velocity that is equal to the component with the highest recorded value [81]: it is calculated by Eq. (10):

$$PPV = Max(V_{Rmax}, V_{Vmax}, V_{Tmax}) \tag{10}$$

4. The maximum vertical component of velocity obtained from measurements or computations [82–86]: it is calculated by Eq. (11):

$$PPV = V_{Vmax} \tag{11}$$

Of the four described approaches, the fourth approach is the best option because it has been used widely in the literature and it includes a better correlation with damage inception. Furthermore, other approaches assume that the maximum velocity components (V_R, V_V, and V_T) occur simultaneously that is far from reality. Consequently, the present study has used the fourth approach to investigate the influence of train-induced velocity on the structural damages of the buildings. Once the numerical analyses of the train track-buildings were performed, the vertical velocity time histories for buildings subjected to the different train movement velocities were plotted. Figure 10 illustrates an example of vertical velocity time histories in the first floor of buildings. It is concluded from this figure that the over-track building A experience higher vertical velocity in comparison with the near-track buildings B and C. In addition, by increasing the distance between the rail track and building, the generated velocity in the buildings were decreased.

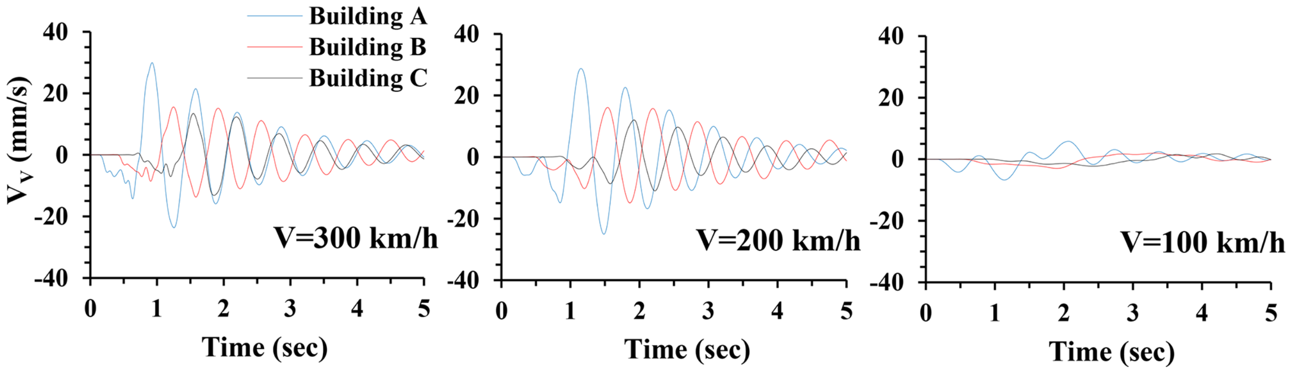

Fig. 10 Vertical velocity time histories for different buildings subjected to train passages with different velocities

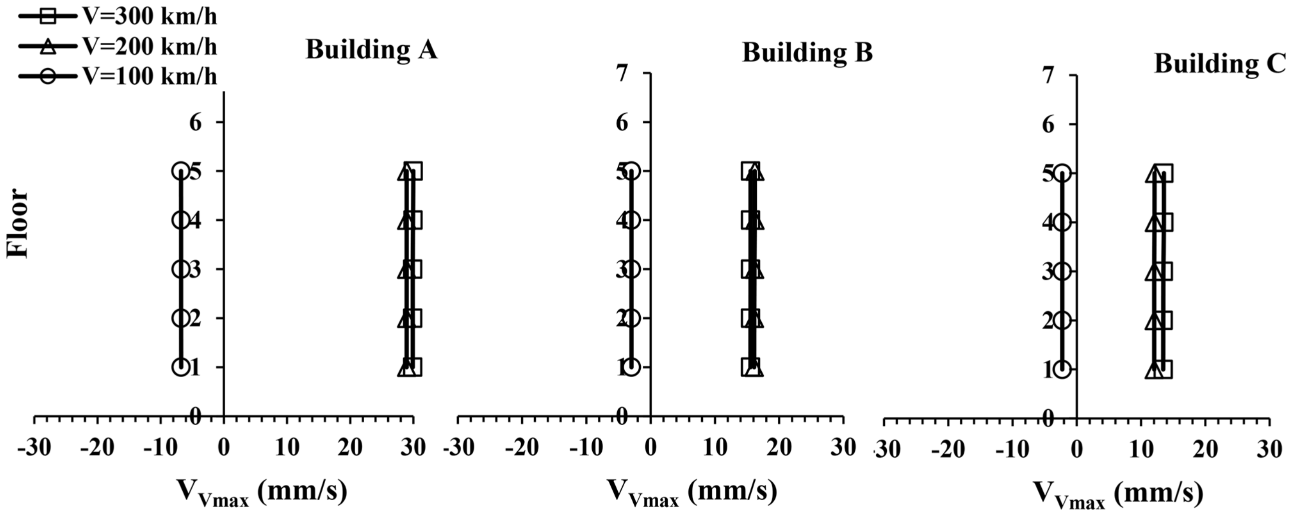

Fig. 11 Maximum V_V on the measuring points of buildings

After plotting all the vertical velocity time histories on the measuring points of buildings shown in Fig. 6, maximum values of V_V were obtained and were shown in Fig. 11.

According to Fig. 11, increment of the train speed results in higher amplitudes of maximum V_V experienced on the floors of buildings. Since the variation of maximum V_V in the floors of buildings is not significant, in the next sections the effect of vibration mitigation technique will be discussed only in the first floors of buildings A, B, and C.

Mitigation of Train-Induced Vibrations with Open Trenches

Numerical Modeling of Open Trench Excavation

The utilization of open trench is an effective method for mitigating the vibrations caused by trains in close proximity to railway lines. Open trench is an excavation in close proximity to the railway tracks, designed to absorb and dissipate the vibrations generated by trains. The utilization of this approach is increasingly being adopted within the fields of urban planning and railway infrastructure projects due to its efficacy in mitigating the propagation of vibrations to adjacent structures. The exploration of the potential of utilizing an open trench as a technique for mitigating vibrations caused by trains on the structural integrity and comfort of buildings in densely populated areas is a topic of interest for civil engineers. A summary of the previous studies to investigate the efficiency of open trenches in dissipating the train-induced vibrations was given in section one.

The primary advantage of employing open trenches as a train-induced vibration mitigation technique, in comparison to alternative methods such as active or passive isolation techniques, lies in its ability to avoid disrupting the flow of train traffic. Furthermore, it is worth noting that the presence of over-track buildings is not significantly impacted by this factor, thereby ensuring their continued serviceability.

In this study, the utilization of rectangular open trenches was chosen as a method to mitigate vibrations, ensuring the comfort of residents and safeguarding buildings against structural damage.

Table 3 Properties of the steel sheet wall

Type of the element in the model	Thickness (m)	Elasticity modulus E (MPa)	Unit weight γ (kN/m^3)	Poisson ratio ν
Elastic Plate	0.01	200×10^3	78.5	0.3

Since the subgrade soil in the models was a soft soil, to prevent the failure of the excavation during the dynamic analyses, a steel sheet wall was modeled and installed on the face of excavation. The interface element was simulated between the steel sheet walls and the subgrade soil to simulate the interaction between these materials. The engineering properties of steel sheet walls are shown in Table 3. Once the excavated trenches were modeled, static analysis was performed to reach the stability of the model. Then, the train motion was simulated by moving points. For the purpose of conducting parametric analyses, a control parameter termed the "Slenderness Ratio" (*d*/*a*) was introduced in this study, where *d* and *a* represent the depth and width of the trench. To evaluate the impact of open trench depth on vibration dissipation, five specific scenarios were considered in this study including: no open trench corresponding to $d/a=0$; and open trenches with a constant width of 1 m but with different depths of 1 m, 2 m, 4 m, and 8 m excavated between the train track and building A. These depths correspond to *d*/*a* ratios of 1, 2, 4, and 8 respectively. It is noted that the distance between the rail track and columns of building A is 3 m. This distance was considered as 6.5 m and 12 m for buildings B and C, respectively. Figure 12 illustrates the excavated open trench and its details in the numerical model.

The Impact of Open Trench Application on Reduction of Train-Induced Vibrations

Open trenches serve as a physical obstruction that effectively mitigates and reduces the vibrations caused by passing trains. The mitigation of vibrations contributes to the development of a more stable and less disruptive inside environment in buildings located in close proximity to train tracks.

In order to evaluate the effect of open trenches on the comfort of residents, a series of parametric analyses were performed on models that adopted trenches of different slenderness ratios. It was shown in Fig. 8 that the discomfort experienced by residents of a building is exclusively influenced by the passage of high-speed trains operating at speeds of 200 km/h and 300 km/h. So, a series of parametric studies were performed in this section to assess the effect of slenderness ratio of the excavated open trenches on the enhancement of residents' comfort in buildings subjected to train passages with speed of 200 km/h and 300 km/h. To ensure the succinctness of the paper, only selective comparison of vertical accelerations time histories obtained at first floor of the buildings have been presented in Fig. 13. According to this figure, the highest vertical acceleration was

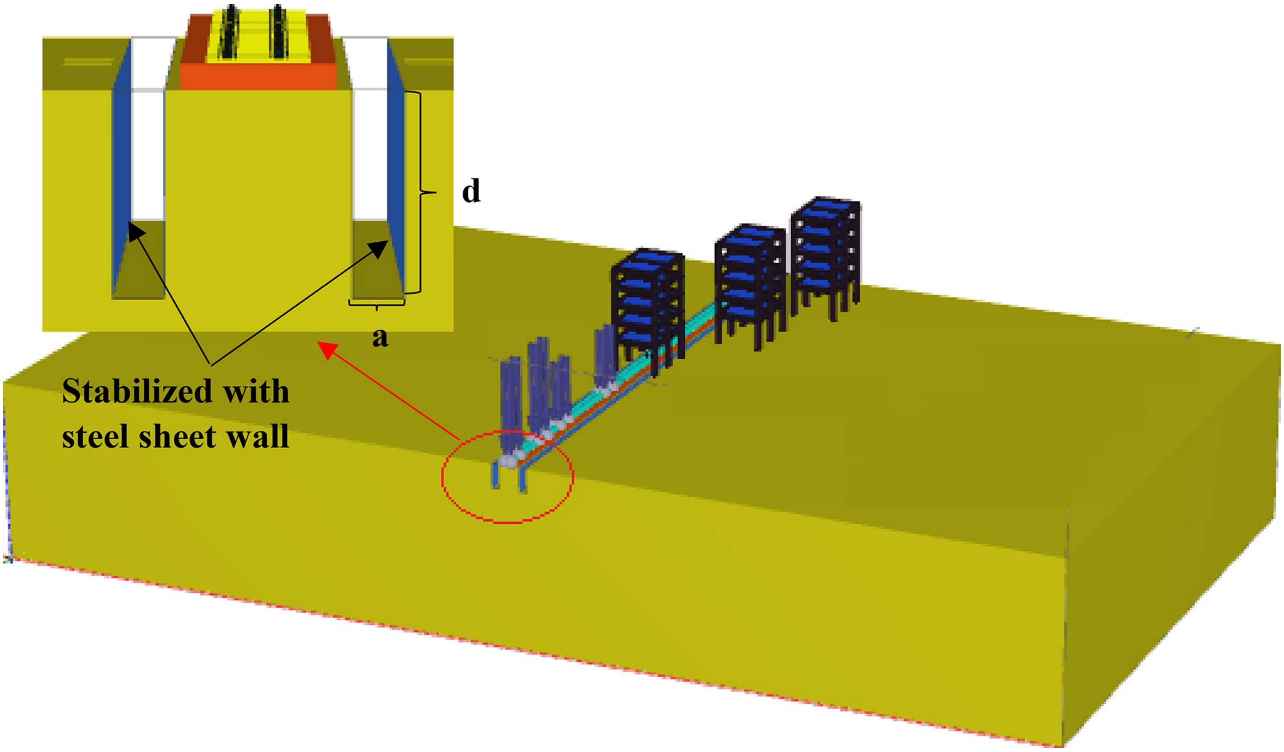

Fig. 12 Open trench application to reduce train-induced vibrations

recorded at the first floor of buildings while no open trench was employed that is for the case of $d/a=0$. By increasing the slenderness ratio, vertical acceleration experienced by the buildings was lowered. Because deeper trenches reduce wave transmission and provide greater isolation from the source of the vibrations.

For example, when the train travels at a speed of 300 km/h, the vertical acceleration recorded on the first floor of the over-track building in the model without an open trench is 4.1 times higher than in the model with an 8-meter deep open trench. Additionally, it was demonstrated that the effectiveness of the employed vibration mitigation technique is more pronounced in the over-track building, as the variation in recorded accelerations in models with different d/a ratios is more noticeable in over-track buildings compared to near-track ones.

The Impact of Open Trench Application on Enhancing the Comfort of Building Residents

It was mentioned in earlier sections that residents of the buildings studied in this paper did not experience any sort of discomfort as a result of the train traveling at $V=100$ km/h. Therefore, models of train-track-buildings were constructed using the open trench method for the scenarios in which trains traveled at speeds of 200 km/h and 300 km/h respectively. In general, 15 numerical models were constructed and analyzed, including models with no open trenches representing $d/a=0$ and models including open trenches with varying slenderness ratios. The a_v results from each of the various buildings were computed and displayed in Figs. 14 and 15. Plotted values were compared with the suggested threshold of a_v = 0.315 m/s^2 in ISO2631-1 to determine the effective *d/a* in the enhancement of residents' levels of comfort that are subjected to train-induced vibration. It should be noted that only results obtained at the first and fifth floors of buildings were shown here.

According to Figs. 14 and 15, increasing the slenderness ratio of open trenches reduces the a_v response recorded on the floors of buildings. Additionally, as the velocity of trains passing near the buildings increases, a deeper open trench will be required to ensure comfort of residents. However, the optimum d/a ratio for resident comfort should be defined for each case. For a train speed of 300 km/h, an open trench with a *d/a* ratio of approximately 6 would be sufficient to ensure.

the comfort of residents in near-track buildings, while a minimum *d/a* ratio of 8 is recommended for the comfort of residents in over-track buildings. For a train speed of 200 km/h, an open trench with a *d/a* ratio of approximately 3 would be sufficient for residents in near-track buildings, while a minimum *d/a* ratio of 4 is recommended to prevent discomfort for residents in over-track buildings.

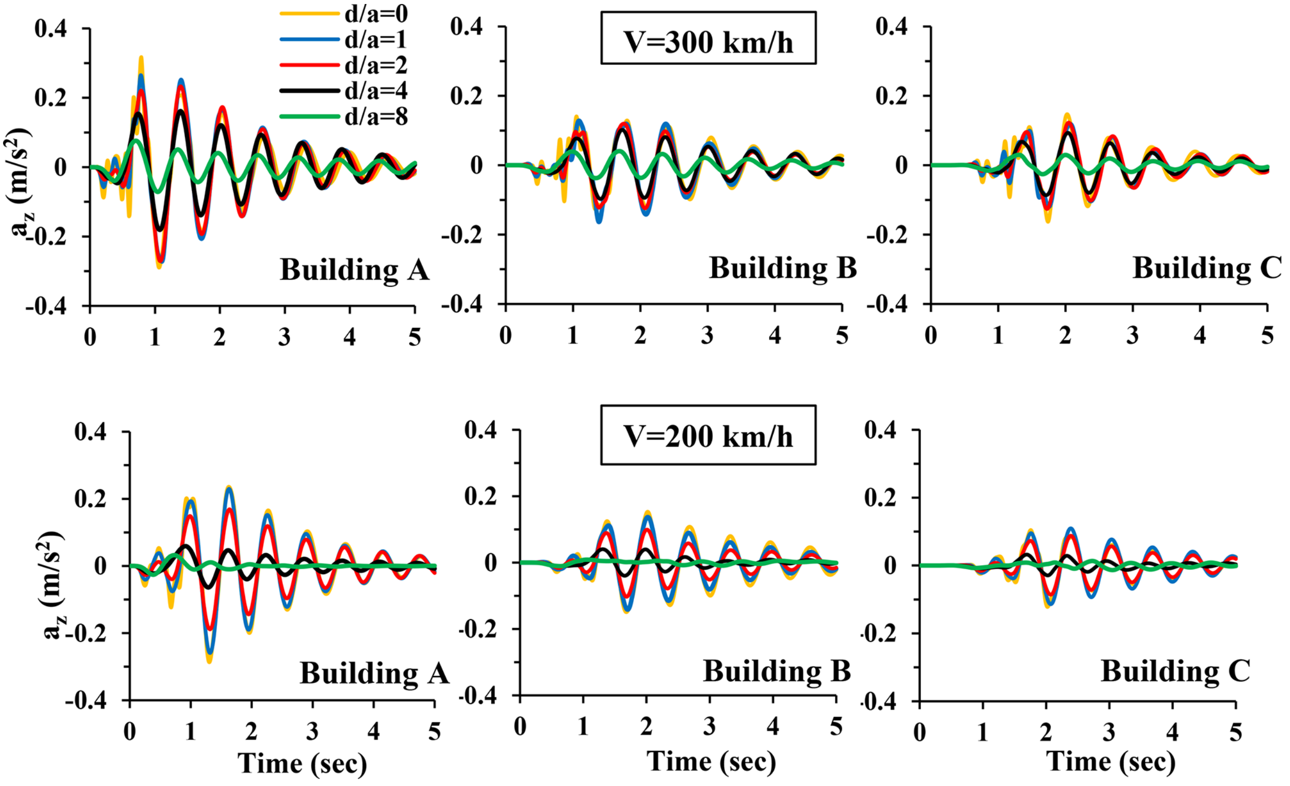

Fig. 13 Influence of different slenderness ratios of open trenches on the reduction of train-induced vibrations

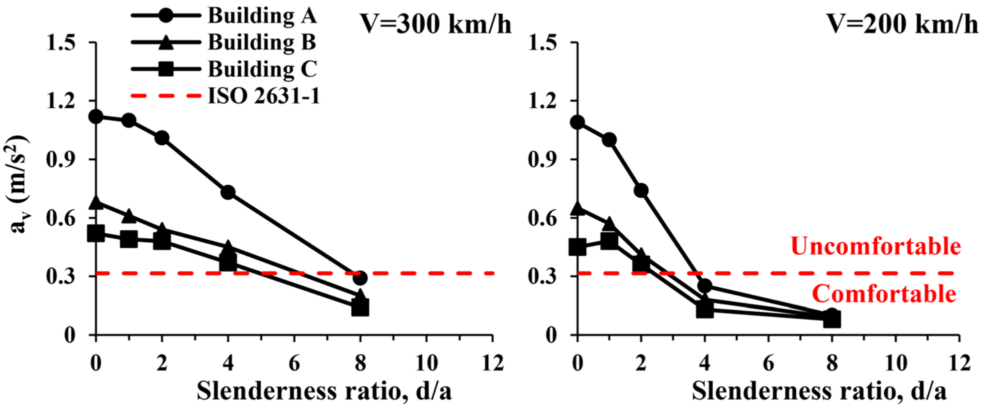

Fig. 14 Effect of the slenderness ratio of open trenches on the comfort level of residents living on the first floor of buildings

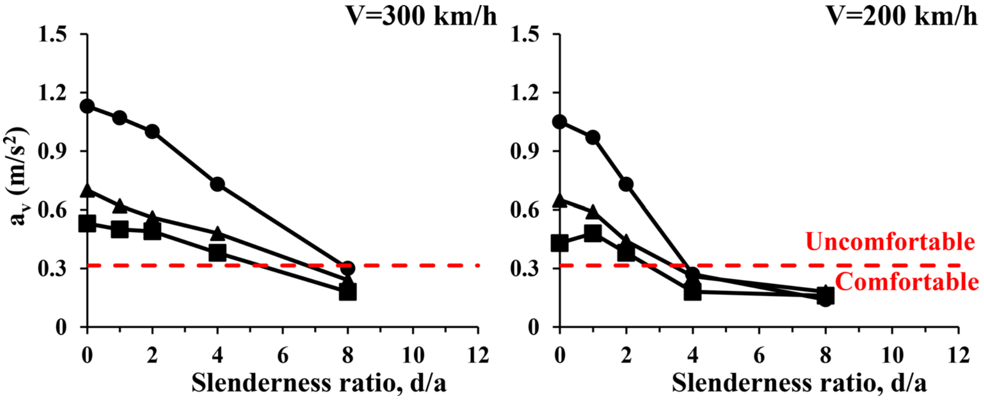

Fig. 15 Effect of the slenderness ratio of open trenches on the comfort level of residents living on the fifth floor of buildings

The Impact of open Trench Application on Preventing the Structural Damage to Buildings

Globally, a variety of standards and guidelines have been developed to define specific requirements for evaluating the potential influence of vibrations on the structural integrity [87–90]. The establishment of these standards is essential in assessing the potential risk of structural damage caused by different sources of vibration, such as construction activities, industrial operations, and transportation systems. These standards specifically define the maximum permissible levels of Peak Particle Velocity (*PPV*), which serves as a critical parameter in this evaluation process. In this section, the efficiency of employing open trenches with different slenderness ratios as a vibration mitigation technique was assessed by comparing the *PPV* values calculated on the first floor of buildings with the permissible *PPV* amplitudes recommended by two different international standards: Eurocode 3 [87] and British Standards [89].

It worth mentioning that to prevent likely damage to residential buildings adjacent to a vibration source, Eurocode 3 and British Standard have suggested maximum allowable *PPV* values of 10 mm/s and 20 mm/s, respectively. Figure 16 presents the effect of the slenderness ratio of open trenches on safety of the studied buildings against structural damage. It's worth noting that the passage of a train at a speed of $V = 100$ km/h did not result in structural damage to either over-track or near-track buildings. In this case, the obtained *PPV* (or V_{Vmax}) is less than 10 mm/s (see Fig. 11). Hence, no vibration mitigation technique is required in this case, and it was not considered in Fig. 16.

Results presented in Fig. 16 can be interpreted through the following scenarios:

When the train speed is 300 km/h:

No open trench: *Building A (PPV = 30 mm/s)*: Eurocode 3 threshold of 10 mm/s and British Standard threshold of 20 mm/s were exceeded. Hence, both standards indicate a high likelihood of structural damage.

Building B (PPV = 15 mm/s) Eurocode 3 threshold of 10 mm/s is exceeded, indicating a potential for structural damage. However, the *PPV* is still below the British Standard threshold of 20 mm/s. British Standard does not anticipate significant damage in this scenario.

Building C (PPV = 13 mm/s) Similar to Building B, Eurocode 3 suggests a potential for structural damage, while British Standard does not indicate significant risk.

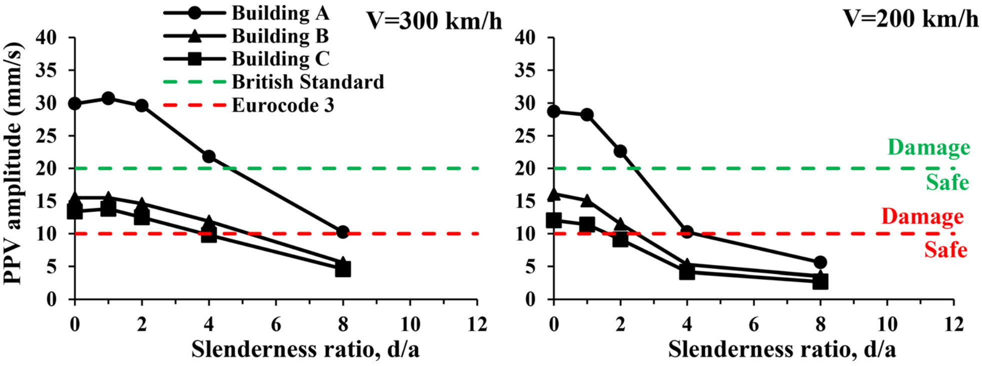

Fig. 16 Effect of the slenderness ratio of open trenches on safety of the studied buildings against structural damage

Open Trench The presence of open trenches with higher slenderness ratios generally reduces the risk of structural damage as indicated by lower *PPV* values.

Building A When utilizing an open trench with a slenderness ratio of 5, it was observed that the *PPV* of 18 mm/s exceeded the threshold specified in Eurocode 3, suggesting the possibility of structural damage. However, the *PPV* remained below the threshold outlined in the British Standard, indicating that the use of an open trench with a slenderness ratio of 5 is effective in improving the safety of buildings. While utilizing an open trench with a slenderness ratio of 8, the *PPV* of 10 mm/s meets the requirements specified by Eurocode 3 and the British Standard. This suggests that there is no significant risk of structural damage.

Buildings B and C When an open trench with a slenderness ratio of 4 was utilized, with a little tolerance, both Eurocode 3 and the British Standard claim that there is no obvious potential for structural damage.

When the train speed was dropped to 200 km/h:
No open trench: *Building A (PPV = 29 mm/s)*: Similar to the case of the train speed of 300 km/h, both standards indicated that the building is prone to vibration-induced damage.

Buildings B and C (PPV = 15 and 12 mm/s) While Eurocode 3 suggests that structural damage is likely as its threshold of 10 mm/s is exceeded, the British Standard indicates no risk of damage to the buildings, as its threshold of 20 mm/s is not exceeded. Therefore, according to the British Standard, the near-track buildings in this study might be considered safe.

Open trench: *Building A*: When utilizing an open trench with a slenderness ratio of 3, it was observed that the *PPV* of 16 mm/s exceeded the threshold specified in Eurocode 3, suggesting the potential of structural damage. However, the *PPV* remained below the threshold outlined in the British Standard, indicating that the use of an open trench with a slenderness ratio of 3 is enough to improve the safety of buildings. While utilizing an open trench with a slenderness ratio of 4, the *PPV* of 10.1 mm/s almost reached the acceptable limit specified by Eurocode 3 and the British Standard.

Buildings B and C When an open trench with a slenderness ratio of 3 was utilized, the calculated *PPV* for buildings B and C were 8 mm/s and 6 mm/s, respectively. These amount of *PPV*s are lower than the permissible value recommended in both standards. So the risk of building damage has been eliminated in this case.

Although the efficiency of using open-trenches in mitigation of train-induced vibrations in buildings has been confirmed in this study, its effectiveness may vary depending on soil conditions and the specific characteristics of the building and surrounding environment. Soil composition and properties play a crucial role in how well the trench absorbs and dissipates vibrations, with softer or looser soils providing less resistance than denser soils. Additionally, factors such as trench depth, width, and distance from the building can influence effectiveness. Buildings with different structural characteristics may also respond differently to the open-trench method. Therefore, a comprehensive understanding of these factors is essential for successful implementation of this technique.

Conclusion

This study involved creating finite element models to simulate the responses of concrete frame buildings located over and near train tracks. The models were used to analyze building responses to trains moving at speeds of 100 km/h, 200 km/h, and 300 km/h. The models were validated using a reference model from the literature, and a parametric analysis was conducted to assess the influence of train speed and distance between the track and buildings on vibrational responses. An intentional train-track irregularity was introduced to evaluate vibrations in the presence of a construction defect. The study compared acceleration and velocity levels with standards like Eurocode 3 and the British Standard to assess safety and comfort. The impact was more pronounced in over-track buildings. Higher train speeds ($V > 100$ km/h) increased discomfort and risk of damage. The effectiveness of the open trench method in reducing vibrations was evaluated, showing that higher slenderness ratios improve structural integrity. For speeds of 200 km/h and 300 km/h, minimum slenderness ratios of 4 and 8, respectively, were recommended to mitigate discomfort and prevent structural damage. Further studies and field investigations are needed to validate these findings.

Understanding the benefits and limitations of using open trenches for mitigating train-induced vibrations in over-track buildings is crucial for informed decision-making and future research. Benefits include significant vibration reduction, improved resident comfort, and minimized structural damage, all without major disruptions to train travel. However, effectiveness can vary with soil conditions and building characteristics. Additionally, construction of open trenches can be labor-intensive and time-consuming, and this method may not completely eliminate vibrations, potentially requiring supplementary measures for optimal results.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s42417-024-01513-x.

Funding Open access funding provided by the Scientific and Technological Research Council of Türkiye (TÜBİTAK).

Declarations

Conflict of Interest No potential conflict of interest was reported by the author.

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