Journal of Civil and Hydraulic Engineering
https://www.acadlore.com/journals/JCHE

Numerical Evaluation of Pile-Driving-Induced Vibrations in Soil and Their Impact on Adjacent Structures

Marwan Abdelsalam, Mohsen Seyedi*

Department of Civil Engineering, School of Engineering and Architecture, Altınbaş University, No: 26, 34218 Bağcılar, Istanbul, Türkiye

* Correspondence: Mohsen Seyedi (mohsen.seyedi@altinbas.edu.tr)

Received: 11-19-2024 **Revised:** 12-10-2024 **Accepted:** 12-19-2024

Citation: M. Abdelsalam and M. Seyedi, "Numerical evaluation of pile-driving-induced vibrations in soil and their impact on adjacent structures," *J. Civ. Hydraul. Eng.*, vol. 3, no. 1, pp. 17–32, 2025. https://doi.org/10.56578/jche030103.

Abstract: In urban environments, the scarcity of available land often necessitates the construction of closely spaced, high-rise buildings, which rely heavily on pile foundations to support substantial loads. However, the pile-driving process, essential for such foundations, generates vibrations that can propagate through the ground and affect surrounding structures, potentially leading to adverse consequences. These vibrations can disrupt the comfort of residents and cause structural damage to adjacent buildings, including residential properties, hotels, and hospitals, where both the comfort and safety of occupants are of paramount importance. Furthermore, pile-driving-induced vibrations can result in the development of cracks in the architecture, settlement of foundations, or even severe structural failure in sensitive installations. To assess the effects of pile-driving on nearby buildings, a series of 77 finite element models were developed using PLAXIS 3D, which simulated varying pile-to-building distances and driving depths. The analyses focused on both the comfort of residents and the structural integrity of adjacent buildings, with comparisons drawn against international standards for vibration levels. The results revealed that the optimal driving depth could effectively minimize peak vibration levels, thereby reducing the risk of disruption to nearby structures. Additionally, the influence of parameters such as pile-driving load, pile penetration depth, and soil characteristics on vibration propagation was systematically explored. The findings provide critical insights into the mitigation of pile-driving-induced vibrations in urban settings and offer guidance for optimizing pile-driving operations to safeguard both resident comfort and structural safety.

Keywords: Plie driving; Resident's comfort; Structural safety; Finite element modeling; PLAXIS 3D; Vibration

1 Introduction

Piles are columnar deep foundation elements made from materials like timber, steel, or concrete, designed to transfer loads and weight of heavy structures through weak, compressible soil or water into stiffer and more stable soil or rock. There are two types of working mechanisms in piles: end bearing, where the load is transferred directly to a stable layer at the pile's tip, and skin friction, where resistance is generated along the sides of the pile as it interacts with the surrounding soil. These mechanisms provide stability and prevent settlement in areas where surface soil alone cannot support the weight of the structure. In tall structures subjected to overturning forces from wind or waves, piles may also carry uplift loads. Marine structures often rely on piles to resist lateral loads from berthing ship impacts and wave forces. Pile driving represents one of the earliest civil engineering practices, with historical examples of timber piles used in bridge construction and riverside settlements in Britain and China (200 BC to AD 200) [1].

The British Standard Code of Practice for Foundations [2] categorizes piles into three types: (i) Large displacement piles, such as solid or closed-end hollow piles, which are driven into the ground and displace soil; (ii) Small displacement piles, driven or jacked into place with a relatively small cross-sectional area, including steel H- or I-sections and open-ended pipes; (iii) Replacement piles, created by removing soil using drilling techniques and filling the hole with concrete.

Piles support major structures worldwide, including towers, high-rise buildings, and bridges. Construction activities like soil excavation, demolition, and vibratory soil compaction can produce vibrations, but the highest levels are typically associated with pile driving in deep foundation construction [3]. While lower than earthquake-induced vibrations, construction-generated vibrations can affect surrounding buildings, potentially disturbing sensitive equipment, people, and causing cracks [4]. Massarsch and Fellenius [5] identified four mechanisms of pile driving damage: (i) static ground movement due to soil displacement, (ii) ground distortion from wave propagation, (iii) settlement and strength loss in loose materials, and (iv) structural damage from dynamic effects. Pile-induced vibrations depend on soil properties, hammer characteristics, and pile attributes, with regulatory limits typically focusing on peak particle velocity (PPV) [6].

In recent decades, numerous numerical and experimental studies have focused on linking vibration limits, human perception, and building damage caused by piling-induced vibrations affecting nearby residents and structures. Whiffin and Leonard [7] associated PPV levels up to 15 mm/s with human discomfort and building damage. The United States Bureau of Mines (USBM) indicated that infrastructure damage could still occur at PPVs ranging from 5.0 mm/s to 50.8 mm/s, depending on the frequency content of the velocity time history [8]. According to German Standards [9], the permissible PPV limit is set at 3 mm/s for foundations and 8 mm/s for upper floors. Another study [10] established vibration limits for four building categories, with maximum PPV values as low as 3.1 mm/s for vibration-sensitive structures, such as historic buildings, and up to 12.7 mm/s for reinforced-concrete buildings.

This paper follows the guidelines of Eurocode 3 [11], which provides detailed categories for total acceleration and PPV measurements. It recommends a maximum allowable acceleration of 0.315 m/s^2 for resident comfort and varying PPV limits, such as 0.5 mm/s for hospitals, libraries, and laboratories, and up to 5 mm/s for other buildings based on construction periods and advance warnings. Additionally, it suggests permissible PPV ranges from 2 mm/s for architectural features to 100 mm/s for buried services.

Theoretically, Attewell and Farmer [12] and Wiss [10] introduced widely used differential equations to estimate PPV as a function of impact energy and radial distance from the vibration source. However, these methods do not provide guidelines for selecting the distance to the driven pile or classifying the impact hammer's energy levels. Massarsch and Fellenius [13] developed a more comprehensive method for predicting piling-induced vibrations, accounting for the applied force at the pile head, dynamic stresses within the pile, and the dynamic resistance along the pile shaft and toe. They also identified three types of vibration waves generated during pile driving: spherical waves originating from the pile toe (primarily P-waves), cylindrical waves due to shear forces along the pile shaft, and surface waves composed of refracted P- and S-waves when they reach the ground surface. This approach allows for the determination of each wave's amplitude and differentiation between vibration sources (pile shaft versus pile toe). Additionally, Massarsch and Fellenius [14] presented a simplified, straightforward method for estimating vibrations without requiring extensive theoretical knowledge. This method assumes that the primary vibration source is at the pile toe and does not account for energy loss between the piling hammer and the pile or the dynamic soil resistance along the pile shaft and toe.

Laboratory-based approaches have been extensively explored in the technical literature to study and estimate vibrations induced by pile driving. Musir and Ghani [15] conducted a scaled laboratory model to examine three key effects impacting the top and bottom of buildings and to identify several physical parameters involved in the propagation of vibration energy affecting adjacent structures. Their results demonstrated that vibrations had a greater impact at the building's base compared to its top and that smaller piles generated more vibrations in nearby structures. Additionally, piles situated closer to buildings produced more significant vibrations than those at greater distances.

Al-Sheakayree et al. [16] and Mahmood and Abdulrahman [17] also utilized experimental scaled laboratory models to investigate the effects of pile driving-induced soil vibrations on existing nearby piles in sandy soil. The analysis of acceleration and PPV data revealed several critical observations: vibration levels increased with higher driving energy and deeper pile penetration. The influence of penetration depth on acceleration and PPV results was found to be more significant than that of driving energy. Furthermore, vibration wave displacement was observed to increase gradually with penetration depth, reaching its maximum in the final third of the pile's embedded length.

Field-based studies on ground vibrations induced by pile driving have been widely reported in the literature. White et al. [18] focused on reducing the adverse impacts of traditional dynamic driving methods for steel tubular piles due to their noise and vibration effects on surrounding environments. They proposed replacing these methods with alternative techniques that minimize human disturbance and building damage. The "Press-in Method" emerged as a favorable alternative, significantly reducing ground vibrations. In one study, three driving methods - diesel hammer, vibratory driving, and press-in pile - were tested at the same site. The press-in pile method produced PPVs ranging from 0.3 to 0.7 mm/s, representing a 10-50 times reduction in ground vibrations compared to traditional methods.

Jaksa et al. [19] investigated and compared PPV measurements from the installation of enlarged-base driven cast-in-situ piles. While boring processes generated less vibration, the maximum PPV recorded during the pressing and expansion of the enlarged base was 8.8 mm/s, a level deemed acceptable for residential areas. Madheswaran and Thandavamoorthy [20] studied the effects of conventional pile driving on existing and newly installed nearby piles for berthing structures in Chennai, India. The maximum vertical acceleration measured on the nearest existing pile head was 20g, significantly exceeding the permissible limit of 0.5g. Additionally, the PPV ranged from 60 mm/s to 100 mm/s, which can disturb neighbors and potentially damage sensitive nearby buildings.

Woods et al. [21] conducted the first attempt to install surface and buried geophones at different depths close to driven piles, providing a comprehensive investigation into the mechanisms of soil vibrations during pile driving. Their findings indicated a moderate increase in acceleration amplitudes at the buried sensors as the pile toe approached within 5 feet above the sensors, followed by a sharp increase when the pile toe reached the depth of the sensors. There was minimal or no shaft contribution to ground motion while the pile toe was above the sensors; however, both shaft and toe contributions combined constructively once the pile toe reached and surpassed the sensor depth. After the pile toe penetrated beyond the sensor level, vibration levels remained relatively constant, likely due to a significant reduction in pile toe contributions as the distance to the sensor increased compared to the pile shaft's influence.

Veshnyakov [22] conducted a field study in Arkhangelsk, Russia, to determine the ratio of peak vertical vibration velocities on the ground surface to those on a building foundation. The study concluded that, for a five-story building on pile foundations situated on stable clay soils, the average ratio of peak vibration velocities between the building foundation and the ground surface was approximately 0.5. Karim et al. [23] investigated the effects of soil vibrations caused by pile driving on surrounding buildings, comparing their findings against the thresholds established by Eurocode 3 [11] and BS5228 [24] standards in Pulau Pinang, Malaysia. Although the contractor adhered to the stipulated limits regarding distance to piling points, frequency limits, building types, and piling methods, five data points exceeded the thresholds. As a result, the authors recommended against using hydraulic hammer piling methods in urban areas, as they may produce vibrations exceeding permissible limits and potentially cause damage to nearby structures.

Recent advancements in finite element method (FEM) computational programs and sophisticated constitutive soil models have significantly enhanced predictive capabilities in geotechnical engineering. The numerous variables inherent to pile driving operations can now be effectively coupled to accurately simulate their impact on urban structures. Shahein et al. [25] conducted a numerical study that combined two distinct finite element analysis software tools. Initially, they used a series of PLAXIS2D models to assess piling-induced PPV at specific points in the surrounding soil. The resulting outputs were then utilized as inputs for SAP2000 to analyze the effect of these PPVs on foundation settlements of a nearby five-story structure. The study demonstrated that significant settlement could occur in clayey and sandy soils at distances of 6 m and 11 m from the piling source, respectively. Madheswaran et al. [26] analyzed peak particle accelerations induced by a piling operation under real conditions using finite element modeling with PLAXIS software. After validating their numerical model results, they examined the influence of concrete trenches on absorbing ground vibrations generated by pile driving. The numerical modeling conducted with PLAXIS showed a tendency to overestimate peak particle accelerations by approximately 20% compared to field data. By analyzing the PPV values from pile driving at different distances, the researchers concluded that the presence of concrete-filled trenches at certain distances could significantly affect the absorption of ground vibrations.

Masoumi et al. [4] conducted a study using a non-linear coupled finite element-boundary element approach to predict free-field vibrations caused by vibratory and impact pile driving using ABAQUS software. This method incorporated both the non-linear constitutive behavior of the soil surrounding the pile and the dynamic interaction between the pile and the soil. By accounting for these factors, the researchers demonstrated that their approach yielded more accurate predictions of ground vibrations, showing much closer agreement with experimental data recorded during vibratory and impact pile driving.

Rezaei et al. [27] investigated the variations in PPV relative to changes in horizontal and vertical distances from the ground surface by simulating continuous pile driving to critical penetration depths using finite element modeling with ABAQUS software. A sensitivity analysis was conducted to evaluate the influence of various parameters on PPV values, including soil properties (e.g., elastic modulus, shear strength) and pile characteristics (e.g., hammer impact force, pile diameter). The results revealed that PPV reached its maximum value at a critical vibration depth of 1 to 5 meters. Additionally, increasing the hammer impact force led to a rise in PPV at all distances, with a 50% increase in impact force resulting in a 26% increase in PPV and a 100% increase leading to a 45% rise. Conversely, an increase in the soil's elastic modulus was associated with a decrease in maximum particle velocity. In summary, these parameters had a significant effect on PPV at closer distances from the pile, while their impact diminished at greater distances.

Noori et al. [28] used PLAXIS2D finite element software to simulate a scaled experimental study, investigating PPV values in clayey soil. Their findings demonstrated a close correlation between the experimental data and numerical simulation results, although the numerical model overestimated PPV values by approximately 21.2% at distances ranging from 10 to 20 meters from the pile. Seyedi [29] employed PLAXIS3D to assess residents' comfort and the structural safety of buildings subjected to train-induced vibrations. The study considered two scenarios: structures in close proximity to and directly over the railway track. It also determined the minimum required depth of open trenches to reduce train-induced vibrations for different building types and train speeds. This paper consolidated various strengths from previous studies, offering a detailed examination of significant aspects of pile driving that had been inadequately addressed. The theoretical framework presented includes reliable calculation methods to estimate PPV as a function of distance from the driven pile.

A 3D finite element model was used to study the effect of horizontal distance and penetration depths during dynamic pile driving on nearby buildings. Seventy-seven PLAXIS3D models were created to analyze the impact of piling-induced vibrations on different floors and the foundation of five-story concrete-framed structures. One novel aspect of this paper was its focus on how these vibrations influence residents' comfort, in addition to building safety. A comprehensive sensitivity analysis was conducted to illustrate how variations in hammer, pile, and soil properties affect structural floors with respect to horizontal distance and pile penetration depths.

2 Methodology

2.1 Vibration Transmission Chain

The entire vibration transfer process from the source to the affected object during pile driving with an impact hammer can be broken down into three main stages, as depicted in Figure 1:

1. Source of Vibrations: The energy generated by the impact of the hammer on the pile head, transferred via the pile cap, is transmitted through the pile. Subsequently, an interaction occurs between the pile and the surrounding soil along the pile shaft and at the pile toe. This pile-soil interaction results in the generation and mobilization of soil vibrations along the pile skin and toe.

2. Wave Propagation in the Soil: The vibrations spread and transmit through the surrounding soil layers.

3. Dynamic Soil-Structure Interaction: This stage encompasses the dynamic response of foundations, vibration amplification within structures, and the impact on buildings.

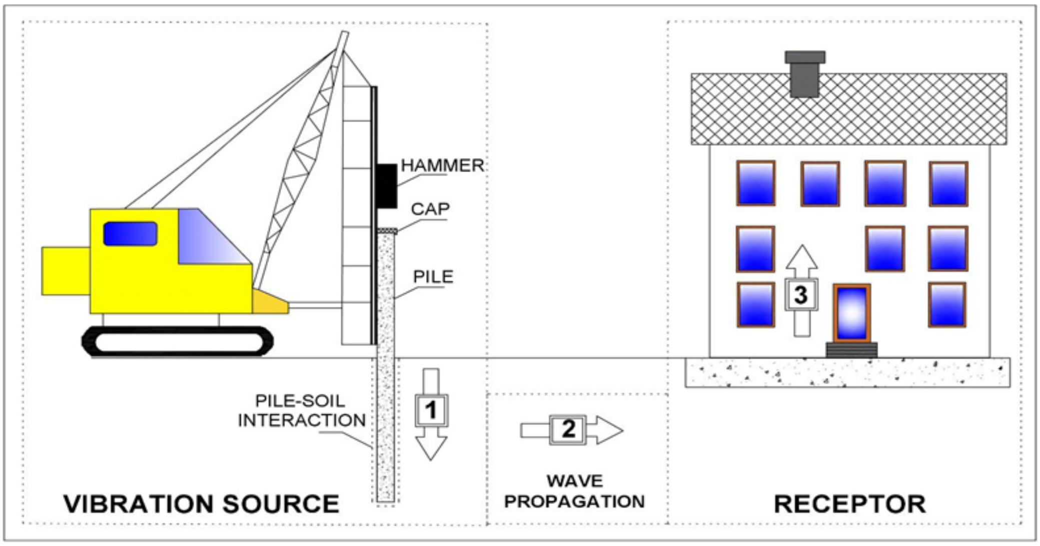


Figure 1. Schematic illustration of the vibration transmission during pile driving

2.2 Description of the Finite Element Model

The representative soil model used is a 100m × 100m × 50m domain of stiff clayey soil, consisting of a single soil layer with the groundwater table located at a depth of 50m below the surface. The soil was modeled using a Hardening Soil Model with Small-Strain Stiffness (HSSMALL), following the PLAXIS3D manual. This soil model presumes that the material behaves elastically during unloading-reloading. However, the strain range over which soils exhibit true elastic behavior - where they nearly fully recover from applied strain - is quite narrow. As the strain amplitude grows, the stiffness of the soil undergoes a nonlinear reduction.

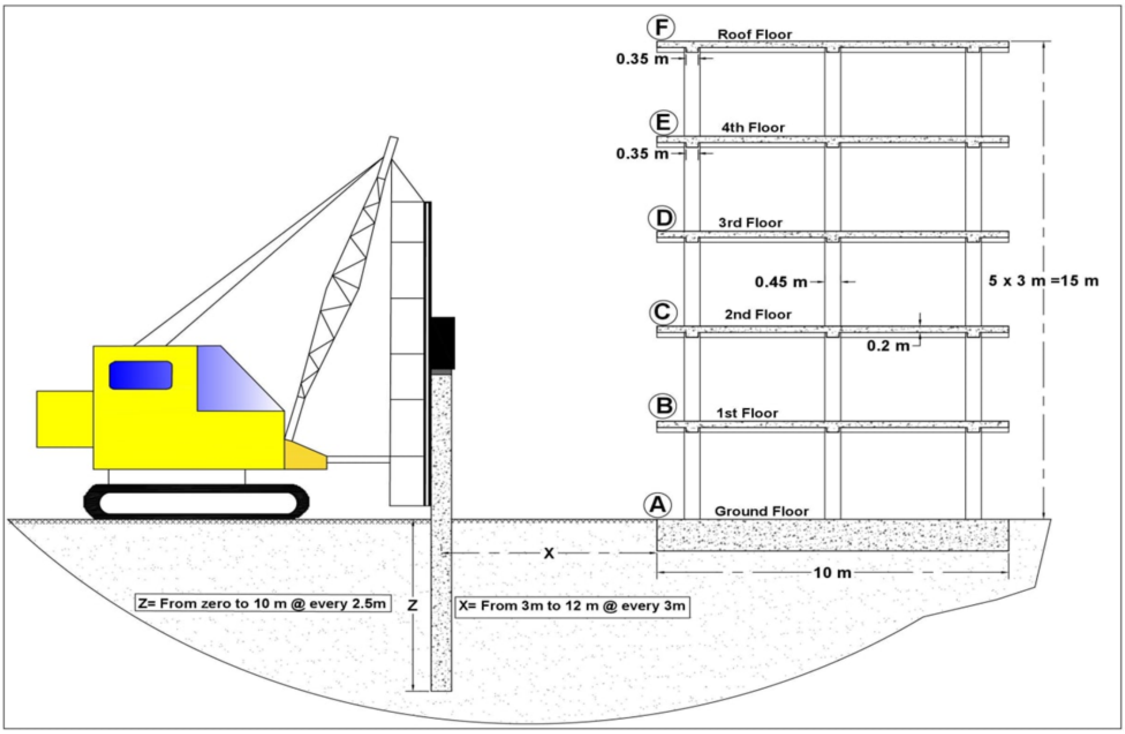
Relevant material properties and details of the model are given in Table 1.

The simplest model commonly used for soil modeling in finite element programs is the Mohr-Coulomb model. This model requires only basic plasticity parameters such as the friction angle and cohesion, as well as elasticity parameters like Young's modulus and Poisson's ratio. Also, unsaturated unit weight, γ_{unsat}, and saturated unit weight, γ_{sat}, of soil are needed as input in finite element programs to accurately model the soil's behavior under varying moisture conditions, affecting its stability, deformation, and response to loading.

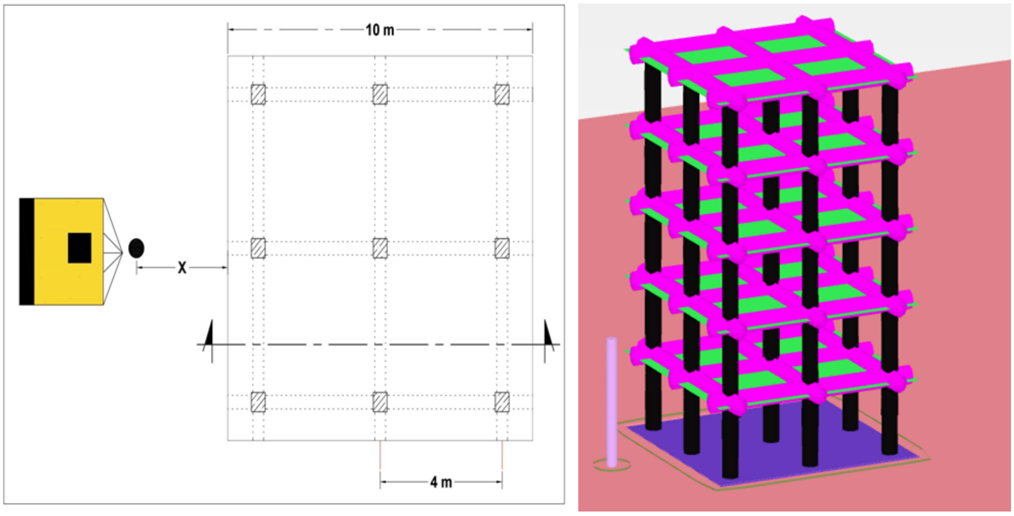
However, it does not accurately capture soil stiffness. To better model this, engineers are encouraged to use more advanced constitutive models, such as the Hardening Soil (HS) model, which more effectively accounts for the variation in soil stiffness under cyclic loading. The HS model simulates changes in soil stiffness with greater precision by incorporating parameters like triaxial loading stiffness, E_{50}, triaxial unloading stiffness, Eur, and oedometer loading stiffness, E_{oed}. In this paper, a modified version of the HS model, known as the HS model with small-strain stiffness (HSsmall), is employed to simulate the soil behavior. The HSsmall model incorporates the increased stiffness of soils at small strains, as soils typically exhibit higher stiffness at low strain levels than at engineering strain levels. This stiffness also varies non-linearly with strain. To capture this behavior, the HSsmall model includes additional strain-history parameters such as $G_{0,ref}$ and $\gamma_{0.7}$. The definition of these parameters is crucial for accurately simulating soil behavior under cyclic loading, and their explanations are provided in Table 1.

Table 1. Parameters of clayey soil

Parameters	Description	Value	Unit
Model	Soil model	HS small	-
Type	Drainage type	Drained	-
γ_{unsat}	Unsaturated unit weight	16	KN/m^3
γ_{sat}	Saturated unit weight	20	kN/m^3
$E_{50, ref}$	Secant stiffness in standard drained triaxial test	20×10^3	kN/m^2
$E_{oed,ref}$	Tangent stiffness for primary oedometer loading	25.61×10^3	kN/m^2
$E_{ur,def}$	Unloading / reloading stiffness	94.84×10^3	kN/m^2
v_{ut}	Poisson's ratio	0.2	-
m	Power for stress-level dependency of stiffness	0.5	-
$G_{0,ref}$	Shear modulus at very small strains	2.7×10^5	kN/m^2
$\gamma_{0.7}$	Shear strain at which $G_s = 0.722G_0$	1.2×10^{-4}	-
c'_{ref}	Cohesion	10	kN/m^2
φ'	Friction angle	18	$^\circ$
ψ	Dilatancy angle	0	$^\circ$



(a)



(b) (c)

Figure 2. Schematic illustration of the simulated building and driving the pile; (a) Side view (b) Plan view (c) 3D view

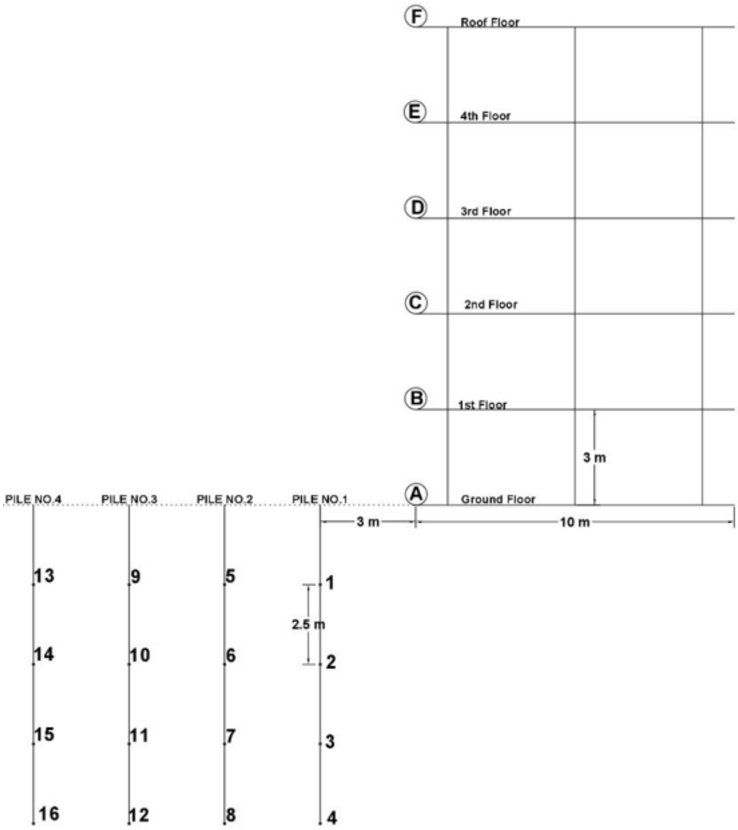


Figure 3. Illustration of different locations for pile driving

Also, a five-story residential building supported on a 10m $\times$ 10m $\times$ 1m mat foundation was simulated. The total height of the building is 15m (5 floors $\times$ 3m each). Slab thickness is 0.2m, beams are sized at 0.35m × 0.35m, and the columns have a cross-section of 0.45m $\times$ 0.50m. All structural members have a unit weight of $\gamma = 25\text{kN/m}^3$ and a stiffness of $\text{E} = 30 \times 106\text{kN/m}^2$. Rayleigh damping factors α and β were set to 0.2320 and 0.008, respectively. This structural model, with these specified dimensions and properties, was verified using another FEM model and found to be safe, showing no self-deflections, cracks, settlements, or damage in the pre-piling stage. In the numerical modeling, the initial conditions, including deformations and stress distributions, were obtained through a plastic analysis during the first phase, which was a static analysis. The bedrock was modeled with a pinned support at the edge, restricting both horizontal and vertical motions. The lateral boundaries were modeled with roller supports, allowing only horizontal motion. All boundaries were considered viscous boundary, which are used in dynamic analysis to absorb outgoing waves and prevent reflections, simulating an unbounded environment for more accurate results. In the second phase, dynamic analysis was conducted by applying the pile driving load.

Table 2. Parameters

Name of Models	Descriptions of the Models	Purpose of the Models	Type of Soil	Pile Prosperities	Dynamic Load (Tons)	No. Models
Preliminary Models	These models were run to describe the dynamic pile driving at sixteen points close to the building. These points express four piles being driven from several horizontal distances ($X = 3, 6, 9$ and 12 m) with various four penetration depths ($Z = 2.5, 5, 7.5$ and 10 m) for each pile (see Figure 3).	Investigation of the effects of piling point's distances and depths on the piling-induced vibrations.	Stiff Clay	$D = 0.5m$ $L = 10m$	20	16
1st round of sensitivity analysis	The previous sixteen models were re-run under the same soil and dynamic load parameters with different pile diameters in order to do the 1st round of sensitivity analysis of piling-induced measurements of building floors with pile diameter variations.	Investigation of the effects of different pile properties and driving distances on the vibration responses in the model.	Stiff Clay	$D = 0.8m$ $L = 10m$	20	16
2nd round of sensitivity analysis	The second batch models above were run with the second duplication of pile diameter to monitor the tendency of piling-induced vibrations of the buildings. Moreover, to emphasize the most effective points and resultant trends as well.		Stiff Clay	$D = 1m$ $L = 10m$	20	16
Ratio of vibration amplitudes in building to the soil	According to the Preliminary model, an additional measurement, point A', was positioned on the soil surface 3 meters beside pile No.1. It is located symmetrically at a 6-meter distance from building foundation of point A (see Figure 4).	Investigation of the measurement ratios of (A/A') at every embedded depth of pile No. 1 at driving points No.1, 2, 3, and 4. (see Figure 3).	Stiff Clay	$D = 0.5m$ $L = 10m$	20	4
Variation of dynamic load models	According to the outputs of the previous 54 models, it was obviously concluded that the most critical penetration depth is 5 meters in the soil that are labeled as points No. 2, 6, 10, and 14 on the piles. Moreover, sensitivity analyses were performed to show the effect of piles penetration depth on the vibration responses. Again, it was shown that the maximum response in the building was recorded when the pile is driven to point 2 in Figure 3. Totally, 7 models were analyzed in this part.	To provide a comprehensive investigation of dynamic load variation effects on the vibration responses in the soil and building.	Stiff Clay	$D = 0.5m$ $L = 10m$	25	7
Variation of soil type models	Under the same parameters of dynamic load and pile properties, a stiff sandy soil with equivalent stiffness was replaced. More 7 models were generated for this purpose by driving piles in depths shown by numbers 1, 2, 3, 4, 6, 10, and 14 (see Figure 3).	To provide a comprehensive investigation of soil properties variations effects on the vibration responses in the soil and building.	Dense Sand	$D = 0.5m$ $L = 10m$	20	7
Variation of groundwater level	Under the same parameters of soil, dynamic load, and pile properties, the groundwater level was raised to the ground surface. More 7 models were generated for this purpose by driving piles in depths shown by numbers 1, 2, 3, 4, 6, 10, and 14 (see Figure 3).	To provide a comprehensive investigation of groundwater level variations effects on the vibration responses in the soil and building.	Stiff Clay	$D = 0.5m$ $L = 10m$	20	7
Ratio of vibration amplitudes in building to the soil	Through the replacement of stiff clay with dense sand, a series of sensitivity analyses were performed to calculate the ratio of vibrations amplitudes in building to the soil.	Investigation of the measurement ratios of (A/A') at every embedded depth of pile No. 1 at driving points No.1, 2, 3, and 4. (see Figure 3).	Dense Sand	$D = 0.5m$ $L = 10m$	20	4
		Total				**77**

The pile used had a diameter of $D = 0.5m$ and a length of $L = 10m$. The nominal weight of the dynamic hammer's ram was 20 tons, resulting in an applied load of $1000kN/m^2$ on the pile cap. The duration of each impact was set to 0.01 seconds to achieve maximum force on the pile, with a fading time (interval between consecutive strikes) of 2 seconds. Schematic illustrations of the simulated building and driving the pile were shown in Figure 2.

The precast concrete pile was driven at varying horizontal distances from the building (3m, 6m, 9m, and 12m) and in varying penetration depths (2.5m, 5m, 7.5m, and 10m), as shown in Figure 3. Measurement points were positioned vertically along a line on each building floor, at the midpoint of the side closest to the pile. Induced vibrations were measured in terms of total acceleration, av, and PPV at 25% increments of penetration depth. The collected data for each floor were analyzed according to thresholds for residents' comfort and potential building damage.

A comprehensive analysis was conducted to evaluate the influence of dynamic load variation, pile parameters, soil properties, and the presence of a water table on the resulting av and PPV values. In total, 77 models were created to provide a detailed depiction of the impact of pile driving-induced vibrations on adjacent structures. Table 2 summarizes key points of these models in detail.

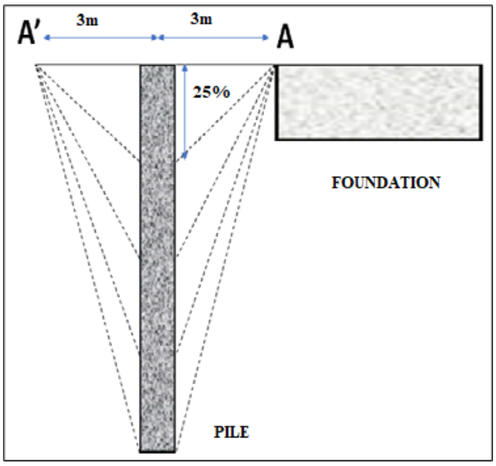


Figure 4. Measurement points on the building and in the soil

2.3 Influence of Piling-Driving Induced Vibration on Buildings Residents' Comfort

As previously noted, vibrations generated by pile driving can have a significant impact on buildings, especially those in close proximity. The well-being and comfort of individuals residing in such buildings are crucial, as pile-driving activities can produce vibrations that greatly disrupt residents' daily lives. Several studies have examined the effects of pile-driving-induced vibrations on buildings [30–32]. According to ISO2631-1 [33], discomfort reactions to vibration environments are determined based on ranges of total resultant acceleration values, av. This standard classifies total vibration acceleration exceeding 0.315m/s^2 as uncomfortable for individuals seated on floors. In this study, acceleration measurements were taken at designated points on each floor. The root-mean-square (rms) acceleration was calculated for each axis, and an appropriate weighting curve was applied [33]. The weighting process was determined using Eq. (1):

$$\mathrm{a_w} = \sqrt{\frac{1}{\mathrm{T}}\sum_{0}^{\mathrm{T}} \mathrm{a_w^2(t)}} \tag{1}$$

where, $a_w(t)$ is the weighted acceleration as a function of time, and T is the duration of measurement in seconds.

Thus, the resultant total acceleration of vibration for each floor is calculated as:

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

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. According to ISO 2631-1, in this study, all the multiplying factors were chosen as 1.

2.4 Influence of Piling-Driving Induced Vibration on Structural Safety

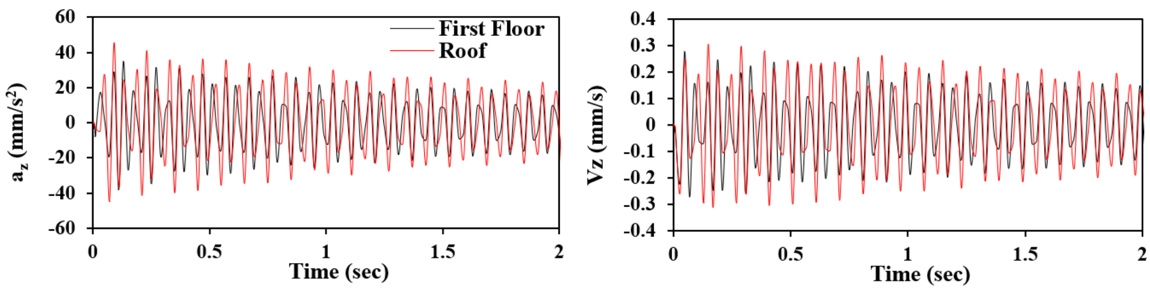
Driving piles in densely populated urban areas can significantly impact the structural integrity of nearby buildings. Over the years, concerns have grown regarding the potential for irreversible damage caused by vibrations from pile driving. Investigating the effects of these vibrations on building stability is critically important, as they can compromise the safety and longevity of adjacent structures. Understanding their impact is essential to implementing proactive measures to protect buildings and ensure the well-being of occupants. To accurately assess pile-driving-induced vibrations in buildings, it is crucial to identify the most effective parameters for evaluation. In recent decades, researchers have demonstrated that PPV is the most reliable criterion for assessing the influence of ground vibrations on structural damage in buildings [34–36]. It should be noted that this research considers the maximum vertical component of velocity obtained on each floor as PPV.

According to Eurocode 3, structural damage is likely when the threshold of 10 mm/s for PPV is exceeded. Therefore, the PPV of each floor was compared against this limit. If the PPV is below 10 mm/s, it can be concluded that the structure is safe from vibrations induced by pile driving.

3 Results and Discussion

3.1 Comparison of Pile-Driving Induced Vibration Components in Building

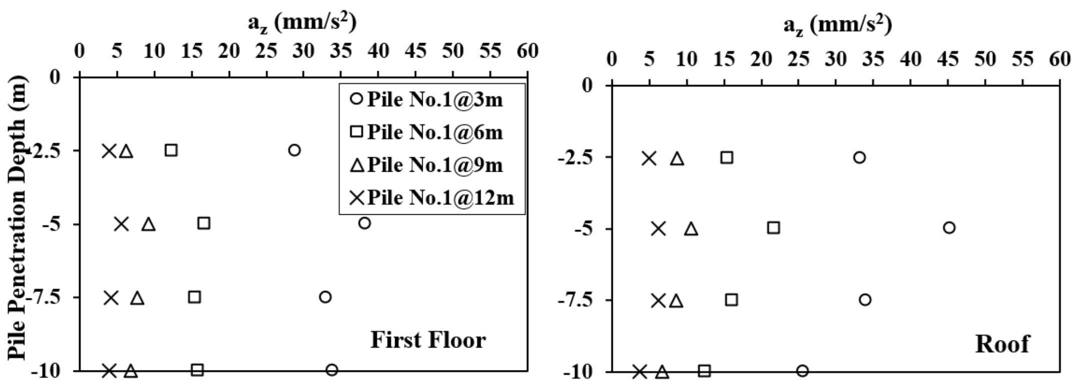
The vibrations induced by pile driving and transmitted to the soil and building are evaluated using the vertical acceleration component, a_z, as well as the vertical velocity component V_z at various measurement points on the building. Following the completion of dynamic analysis for different pile driving distances, pile diameters, and pile depths, the velocity and acceleration time histories for the building were recorded. It is important to note that, out of 77 numerical simulations, the scenario with a 5m pile diameter, a 3m distance from the building, and a 5m driving depth (pile No. 1 in Figure 3) produced the critical vibration components. To keep the discussion concise, only the results relevant to this analysis are presented in this research. Figure 5 shows a comparison of the vertical velocity and acceleration components measured on the building's first floor and roof. It illustrates that vibrations induced by pile driving are transmitted from the soil to the building floors.



(a) (b)

Figure 5. Comparison of the pile-driving induced vibrations recorded on first floor and roof of the building (5m pile diameter, a 3m distance from the building, and a 5m driving depth)

3.2 Influence of the pile Distance on the Pile-Driving Induced Vibration in Building



(a) (b)

Figure 6. Vertical accelerations induced by pile driving, as recorded on the first floor and roof of the building

Figure 6 compares the vertical acceleration induced by pile driving, as recorded on the first floor and roof of the building, for various pile driving distances from the building. It is inferred from the figure that increasing the distance between the pile driving point and the building reduces the transmitted vibration because vibration intensity decreases with distance due to the spreading of energy over a larger area. When piles are driven, the resulting seismic waves travel through the ground and radiate outward. As these waves move farther from the source, their energy dissipates, leading to a reduction in their amplitude and impact. The soil properties also play a role; at greater distances, the ground's ability to absorb and dissipate energy increases, further mitigating the vibrations that reach the building. It is also concluded that the higher amplitude of vibrations was recorded when the penetration depth of the piles was 5m.

Figure 7 illustrates the impact of pile driving depth and its distance from the building on the horizontal acceleration recorded on the building's first floor. The results show that as the pile driving depth increases, the acceleration transferred to the building decreases. This is attributed to the damping effect of the soil, which reduces the generated vibrations and lowers the wave amplitude as it propagates from deeper layers to the surface. Additionally, increasing the distance between the pile driving point and the building also results in a reduction of the transmitted vibrations to the building.

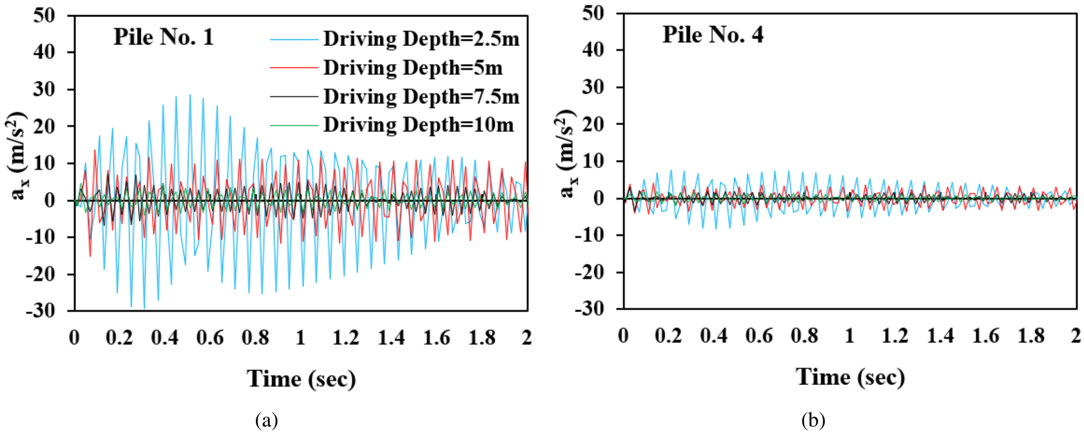


Figure 7. Effect of pile driving depth and its distance from the building on the horizontal acceleration recorded in the first floor of the building

3.3 Influence of the Pile Diameter on the Pile-Driving Induced Vibration in Building

Figure 8 examines the impact of driven pile diameter on the transmitted acceleration recorded on the first floor of the building. In this case, the distance between the pile and the building is set at 3 meters, which represents the most critical scenario. According to this figure, increasing the diameter of a driven pile can reduce the transmitted vibration to the building because larger piles tend to generate lower levels of ground vibration compared to smaller piles. This is because a larger pile has a greater surface area in contact with the surrounding soil, which helps distribute the energy from pile driving over a wider region. As a result, the energy is less concentrated, and the intensity of the vibrations that travel through the ground and reach the building is diminished. Additionally, larger piles typically experience less deformation under the impact of driving, leading to a reduction in the amount of energy transmitted to the surrounding soil.

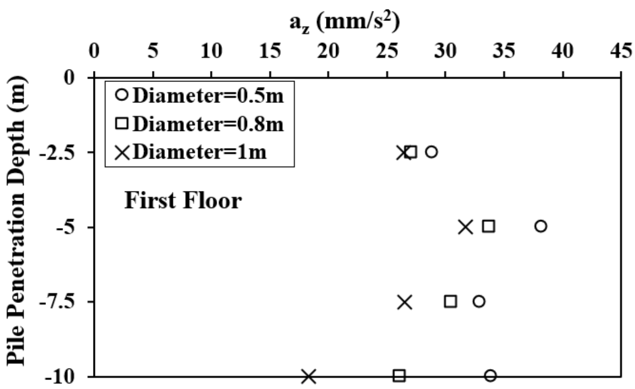


Figure 8. Effect of changes in pile diameter on the vibration components transmitted and recorded within the building

3.4 Influence of the Applied Driving Load on the Pile-Driving Induced Vibration in Building

Figure 9 examines the impact of the driving load on a pile on the transmitted acceleration recorded on the first floor of the building. It is concluded that increasing the driving load on a pile typically results in greater transmitted vibration to the building because a higher driving load generates more energy during the pile installation process. When a pile is driven into the ground, the impact force from the hammer causes vibrations that travel through the soil and reach nearby structures. A higher driving load increases the intensity of these vibrations, as the force applied to the pile is greater, leading to larger ground movements. These intensified vibrations are then transmitted through the surrounding soil to the building. For instance, when the pile penetration depth is 5 meters, increasing the load from 20 tons to 25 tons resulted in a 13% increase in the transmitted acceleration.

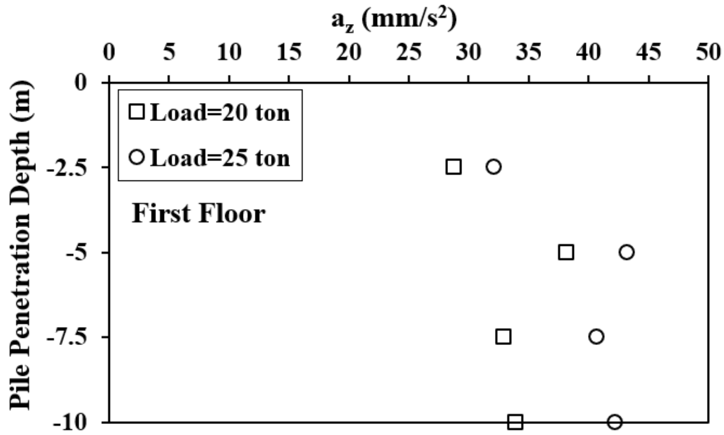


Figure 9. Impact of increasing driving load on vibration transmission to building structures

Figure 10 compares the vertical acceleration induced by pile driving on the first floor of the building, considering variations in the applied driving load and the distance of the driving points from the building. The results show that a higher driving load leads to a stronger vibration response in the building. Additionally, increasing the distance between the driving point and the building reduces the vibration response. Furthermore, increasing the driving load when the driving point is far from the building has little effect on the vibration response.

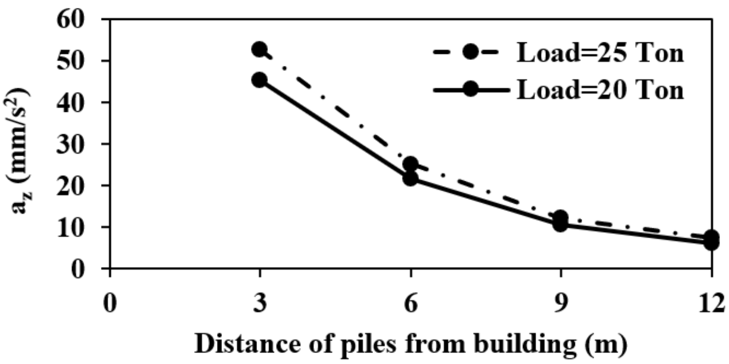


Figure 10. Influence of the applied driving load on the pile-driving induced vibration in building

3.5 Influence of the Soil Type on the Pile-Driving Induced Vibration in Building

Figure 11 compares the pile-driving-induced vibration transmission to the building constructed on clay and sand layers. Soil type plays a key role in the transmission of vibrations from pile driving to buildings. Vibrations are typically stronger in sandy soils than in clay due to differences in their mechanical properties. Sand, being loose and granular, allows vibrations to travel more easily and efficiently, transmitting higher levels of energy to nearby buildings. In contrast, clay, with its denser and more cohesive structure, absorbs and dampens these vibrations, reducing their impact on the building.

These results align with earlier published studies. Figure 12 displays a numerical analysis from the literature [37], which demonstrates that changes in soil properties, such as friction angle and cohesion, influence the ground vibration response caused by pile driving. This effect is more significant at locations closer to the pile driving points.

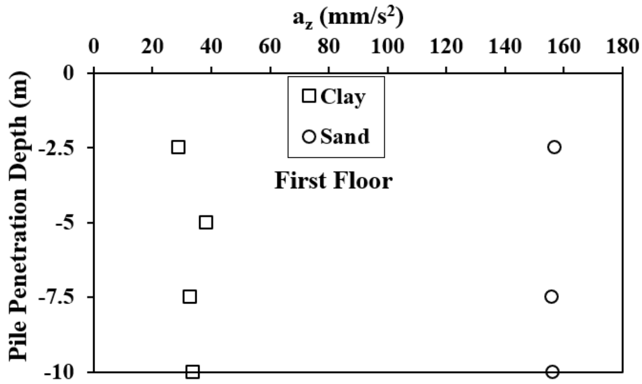
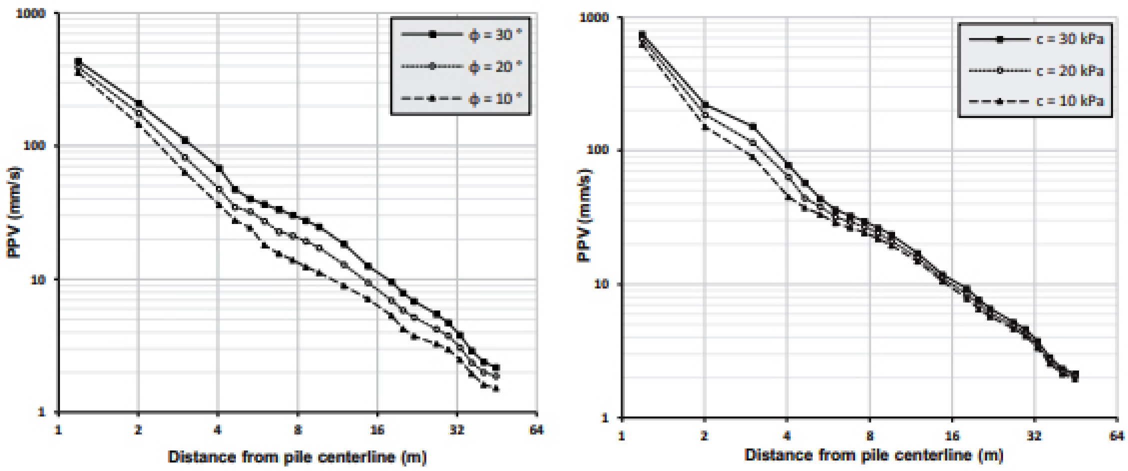


Figure 11. Influence of the soil type on the pile-driving induced vibration in building



(a)

(b)

Figure 12. Evaluation of the effect of variation in soil properties on pile driving-induced ground vibrations [37]

3.6 Influence of the Existence of Water in Soil on the Pile-Driving Induced Vibration in Building

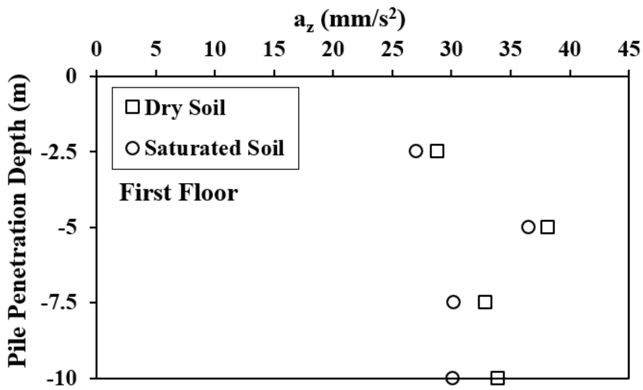


Figure 13. Comparisons between the acceleration responses in building due to the pile driving in dry and saturated soils

When pile driving induces vibrations in the soil, the energy from these vibrations is transmitted through the surrounding medium, including the water present in the pore spaces of the soil. As the pile moves, it generates rapid changes in pressure within the pore water, causing an increase in pore water pressure. This increase in pressure acts as a form of energy dissipation, converting the vibrational energy into thermal energy through internal friction within the fluid. Essentially, the pore water pressure increment reduces the amplitude of the vibrations by absorbing and dissipating the energy, preventing it from propagating efficiently through the soil to adjacent structures. The rate at which this dissipation occurs depends on the soil's permeability and the ability of the water to move through the soil, with less permeable soils resulting in higher pore pressure buildup and greater energy dissipation. This mechanism helps to reduce the transmission of harmful vibrations to surrounding buildings and the environment.

Figure 13 compares the vertical acceleration induced by pile driving in dry and saturated soils to assess the impact of moisture on the transmission of vibrations from the source to the building. The results indicate that vibrational wave propagation is more efficient in dry soil than in saturated soil.

3.7 Influence of Pile-Driving Induced Vibration on Buildings Residents' Comfort

After completing the dynamic analyses, the total acceleration responses caused by pile driving were calculated for both the ground level and the roofs of buildings constructed on clay and sand, using Eq. (2). This procedure involves several steps. First, the time histories of horizontal and vertical acceleration induced by pile driving (a_{wx}, a_{wy}, and a_{wz}) were obtained. Next, the square of these time histories was calculated for each time step. In the following step, these squared values were multiplied by the corresponding squared multiplying factors (k_x, k_y, and k_z), yielding the result $a_v = \sqrt{k_x^2 a_{wx}^2 + k_y^2 a_{wy}^2 + k_z^2 a_{wz}^2}$. ISO 2631-1 is an international standard that defines various levels of vibration effects on the human body. According to this standard, a vibrational acceleration exceeding $av = 0.315 m/s^2$ will cause discomfort to humans. Therefore, the calculated av responses for each model were compared to the threshold of $0.315 m/s^2$, as recommended by ISO 2631-1.

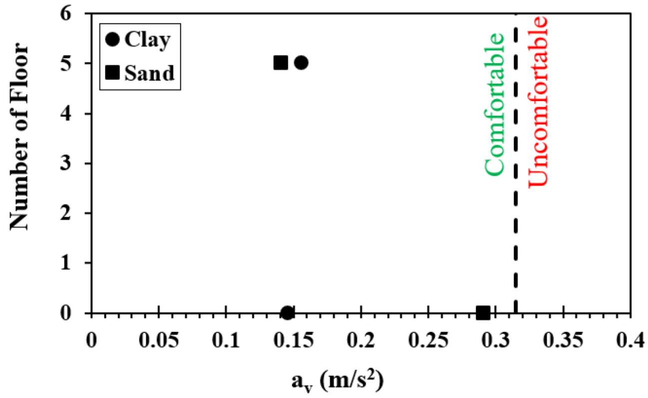


Figure 14. Comparing the total acceleration induced by pile-driving in building with the comfort threshold specified by ISO 2631-1

As shown in Figure 14, all results fall within the comfortable zone, indicating that the vibrations induced by pile driving did not disrupt the building's residents, provided the pile-driving location is at least 3 meters away from the building.

3.8 Influence of Pile-Driving Induced Vibration on Structural Safety

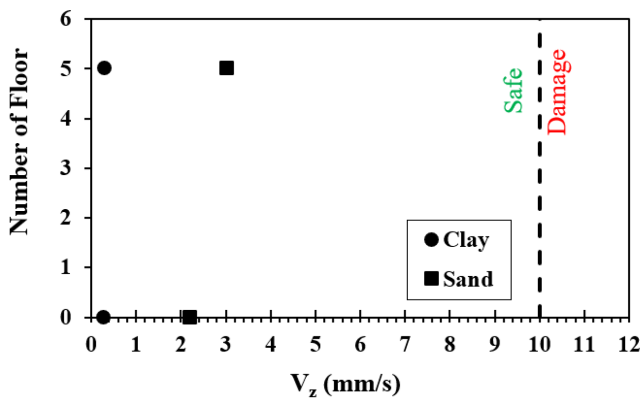


Figure 15. Comparing the vertical velocity induced by pile-driving in building with the safety limit specified by Eurocode 3

As mentioned earlier, the PPV (referred to as the maximum vertical component of velocity, Vz, in this study) measured on the floors of a building exposed to vibration is a valuable parameter for assessing the safety and integrity of the structure. Several studies in the literature have utilized this parameter to evaluate structural safety in response to vibrations [14, 30–32, 38]. The same approach was applied in this study.

After completing the dynamic analyses, the vertical velocity responses caused by pile driving were calculated for both the ground level and the roofs of buildings constructed on clay and sand. These responses were then compared to the threshold of 10 mm/s, as recommended by Eurocode 3. As shown in Figure 15, all results fall within the safety zone, indicating that the vibrations induced by pile driving did not cause any structural damage to the building.

4 Conclusions

The results of the dynamic analysis of pile-driving-induced vibrations reveal several key factors that influence the intensity of vibrations transmitted to buildings. Vertical acceleration and velocity components were recorded at various points on the building, demonstrating how these vibrations propagate through the soil and structure. The study found that increasing the distance between the pile-driving point and the building generally reduced the transmitted vibrations, as the energy from the seismic waves dissipated with distance. Additionally, larger pile diameters and reduced driving loads were found to lower the intensity of transmitted vibrations, as these factors helped spread the energy over a larger area and reduced soil deformation.

The type of soil significantly impacted vibration transmission, with sandy soils allowing vibrations to travel more efficiently and generating stronger impacts on buildings compared to clay soils, which absorb and dampen the energy. The presence of water in the soil further mitigated vibrations, with saturated soils reducing the transmission efficiency due to the dampening effect of water between soil particles.

When comparing the total acceleration responses to the comfort threshold of 0.315 m/s^2 (as per ISO 2631-1), and the vertical velocity responses to the safety threshold of 10 mm/s (as per Eurocode 3), all results fell within the acceptable limits. This indicates that, under the conditions analyzed-such as pile-driving distances of at least 3 meters from the building-vibrations did not exceed levels that would affect occupant comfort or cause structural damage. Therefore, the study confirms that pile driving, when conducted with proper distance, pile size, and load management, is unlikely to disrupt building residents or cause harm to the structure.

While the numerical models provided valuable insights into the effects of pile driving-induced vibrations on the ground, adjacent buildings, and residents' comfort, there are several limitations to this study. The 2D model used in this analysis simplifies the complex interactions in the real-world 3D environment, which may lead to underestimations or overestimations of the vibrational impacts, particularly in heterogeneous soils or irregular building layouts. Additionally, the model assumes uniform soil properties, which may not accurately reflect variations in real-world conditions, such as differences in soil type, moisture content, and stratigraphy. Furthermore, this did not account for factors such as varying pile types, vibration frequencies, or long-term effects on soil and structure behavior.

Future research should aim to refine the model by incorporating 3D simulations to better capture the complexity of wave propagation in various soil types and environmental conditions. Including more detailed soil characteristics, such as layering, permeability, and dynamic properties, would enhance the model's accuracy. Additionally, extending the analysis to consider different pile materials, pile sizes, and vibration frequencies would provide a more comprehensive understanding of the factors influencing vibration transmission. Incorporating the potential effects of time, such as soil compaction or long-term building settlement, could further improve the model's predictive capabilities for real-world applications, ensuring more accurate assessments of vibration impacts on human comfort and structural integrity.

Data Availability

Not applicable.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] M. Tomlinson and J. Woodward, *Pile Design and Construction Practice*. CRC Press, 2007.

[2] British Standards Institution, *Evaluation and Measurement for Vibration in Buildings. Part 2: Guide to Damage Levels from Groundborne Vibration*, London, 1993.

[3] A. Colaço, M. A. Ferreira, and P. A. Costa, "Empirical, experimental and numerical prediction of ground-borne vibrations induced by impact pile driving," *Vibration*, vol. 5, no. 1, pp. 80–595, 2022. https://doi.org/10.3390/vibration5010004

[4] H. R. Masoumi, S. François, and G. Degrande, "A non-linear coupled finite element-boundary element model for the prediction of vibrations due to vibratory and impact pile driving," *Int. J. Numer. Anal. Methods Geomech.*, vol. 33, no. 2, pp. 245–274, 2009. https://doi.org/10.1002/nag.719

[5] K. R. Massarsch and B. Fellenius, "Ground vibrations from pile and sheet pile driving," in *Proceedings of the DFI-EFFC International Conference on Piling and Deep Foundations*, 2014, pp. 131–138.

[6] H. Saher, H. Al-Jubair, and J. Alsalaet, "Measurements of induced vibrations due to steel pipe pile driving in Al-Fao soil: Effect of partial end closure," *Open Eng.*, vol. 14, no. 1, pp. 1–14, 2024. https://doi.org/10.1515/eng-2022-0550

[7] A. C. Whiffin and D. R. Leonard, *A Survey of Traffic-induced Vibrations*. Road Research Laboratory, 1971.

[8] D. Siskind, M. Stagg, J. Kopp, and C. Dowding, *Structure Response and Damage Produced by Ground Vibration from Surface Mine Blasting*. US Department of the Interior, Bureau of Mines, 1980.

[9] DIN (German Institute for Standardization), *Structural Vibration–Part 3: Effects of Vibration on Structures*. DIN 4150-3, Berlin, 1999.

[10] J. F. Wiss, "Construction vibrations: State-of-the-art," *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.*, vol. 18, no. 4, p. 63, 1981. https://doi.org/10.1016/0148-9062(81)91206-7

[11] CEN (European Committee for Standardization), *Design of Steel Structures: Part 5: Piling*. Eurocode 3, ENV 5, Brussels, Belgium, 1993.

[12] P. B. Attewell and I. W. Farmer, "Modern piling: Part two-attenuation of ground vibrations from pile driving," *Ground Eng.*, pp. 26–29, 1973.

[13] K. R. Massarsch and B. H. Fellenius, "Ground vibrations induced by impact pile driving," in *International Conference on Case Histories in Geotechnical Engineering*. Missouri University of Science and Technology, 2008.

[14] K. R. Massarsch and B. H. Fellenius, "Engineering assessment of ground vibrations caused by impact pile driving," *Geotech. Eng. J. SEAGS AGSSEA*, vol. 46, no. 2, pp. 54–63, 2015. https://scholarsmine.mst.edu/icchge/6icchge/session12/3

[15] A. A. Musir and A. N. A. Ghani, "A study of pile driving effects on nearby building," *Int. J. of GEOMATE*, vol. 6, no. 1, pp. 806–810, 2014.

[16] T. K. Q. Al-Sheakayree, Q. S. M. Shafiqu, and A. T. Ibraheem, "The dynamic effect of pile installation in sand on nearby piles," *Al-Nahrain J. Eng. Sci.*, vol. 20, no. 2, pp. 477–485, 2017.

[17] R. M. Mahmood and S. H. M. Abdulrahman, "Characteristics of vibration wave transmission within the soil due to driving precast concrete pile," *Int J Curr. Eng. Technol.*, vol. 7, no. 6, pp. 2104–2108, 2017. https://doi.org/10.1201/9781003209379-56

[18] D. White, T. Finlay, M. Bolton, and G. Bearss, "Press-in piling: Ground vibration and noise during pile installation," in *Deep Foundations 2002: An International Perspective on Theory, Design, Construction, and Performance*, 2002. https://doi.org/10.1061/40601(256)26

[19] M. Jaksa, M. Griffith, and R. Grounds, "Ground vibrations associated with installing enlarged-base driven cast-in-situ piles," *Aust. Geomech.*, vol. 37, pp. 67–73, 2002.

[20] C. K. Madheswaran and T. S. Thandavamoorthy, "Field investigation on ground and structural vibrations during prototype pile driving," in *International Conference on Case Histories in Geotechnical Engineering*, 2004. https://scholarsmine.mst.edu/icchge/5icchge/session04/19

[21] R. Woods, A. Zekkos, A. Grizi, A. Pietrangelo, and A. Zimmerman, "Measurement of ground motion near piles during driving," in *From Soil Behavior Fundamentals to Innovations in Geotechnical Engineering*, 2014. https://doi.org/10.1061/9780784413265.041

[22] V. A. Veshnyakov, "Investigation of ground and foundation vibrations of an existing building during impact pile driving," *IOP Conf. Ser.: Mater. Sci. Eng.*, vol. 945, p. 012055, 2020. https://doi.org/10.1088/1757-899X/945/1/012055

[23] N. A. Karim, A. A. Musir, M. S. A. Hamid, S. H. Hassan, A. I. Q. Kamarulzaman, and M. F. A. Majid, "The effect of vibration impact from piling works to the surrounding buildings," *Civ. Eng. Archit.*, vol. 9, no. 5A, pp. 101–107, 2021. https://doi.org/10.13189/cea.2021.091312

[24] British Standards Institution, "Code of practice for noise and vibration control on construction and open sites–Part 2: Vibration," 2009.

[25] M. Shahein, A. Farouk, and M. Ramadan, "The effect of pile driving on soil and adjacent structure response-numerical study," in *Ninth Alexandria International Conference on Structural and Geotechnical Engineering*, 2016.

[26] C. Madheswaran, K. Natarajan, R. Sundaravadivelu, and A. Boominathan, "Effect of trenches on attenuation of ground vibration during pile driving," in *Vibration Problems ICOVP-2007*, 2008, pp. 231–238. https:

//doi.org/10.1007/978-1-4020-9100-1_24

[27] M. Rezaei, A. Hamidi, and A. F. Homayoun Rooz, "Investigation of peak particle velocity variations during impact pile driving rrocess," *Civ. Eng. Infrastruct. J.*, vol. 49, pp. 59–69, 2016. https://doi.org/10.7508/ceij.2016.01.005

[28] H. S. Noori, R. Shirinabadi, E. Moosavi, and M. Gholinejad, "Effect of pile driving on ground vibration in clay soil: Numerical and experimental study," *Geotech. Geol. Eng.*, vol. 40, no. 4, pp. 2051–2062, 2022. https://doi.org/10.1007/s10706-021-02010-8

[29] M. Seyedi, "Impact of train-induced vibrations on residents' comfort and structural damages in buildings," *J. Vib. Eng. Technol.*, 2024. https://doi.org/10.1007/s42417-024-01513-x

[30] M. S. Serdaroglu, "Nonlinear analysis of pile driving and ground vibrations in saturated cohesive soils using the finite element method," Ph.D. dissertation, University of Iowa: Iowa City, IA, 2010. https://doi.org/10.17077/etd.rtrwh6t6

[31] B. Schumann and J. Grabe, "FE-based modelling of pile driving in saturated soils," in *Proceedings of the 8th International Conference on Structural Dynamics, EURODYN 2011*, Leuven, Belgium, 2011. https://hdl.handle.net/11420/46699

[32] G. A. Athanasopoulos, R. D. Woods, and A. Grizi, "Effect of pile-driving induced vibrations on nearby structures and other assets," Michigan DOT, Lansing, MI, ORBP Number OR10-046, Tech. Rep., 2013. https://rosap.ntl.bts.gov/view/dot/27160/dot_27160_DS1.pdf

[33] ISO 2631-1, "Mechanical vibration and shock: Evaluation of human exposure to whole-body vibration. Part 1, General Requirements," International Standard, Tech. Rep., 1997.

[34] K. R. Massarsch and B. B. Broms, "Damage criteria for small amplitude ground vibrations," in *2nd International Conference on Recent Advances in Geotechnical Earthquake Engineering and Soil Dynamics*. University of Missouri–Rolla, 1991, pp. 1451–1459. https://scholarsmine.mst.edu/icrageesd/02icrageesd/session11/6

[35] S. Jones, *Transportation and Construction-Induced Vibration Guidance Manual*. Calif Department of Transport, Noise, Vibration, and Hazardous Waste Management Office, Sacramento, Calif, 2004.

[36] M. R. Svinkin, "Minimizing construction vibration effects," *Pract. Periodical Struct. Des. Constr.*, vol. 9, no. 2, pp. 108–115, 2004. https://doi.org/10.1061/(ASCE)1084-0680(2004)9:2(108)

[37] A. Farshi Homayoun Rooz and A. Hamidi, "Numerical analysis of factors affecting ground vibrations due to continuous impact pile driving," *Int J Geomech*, vol. 17, no. 12, p. 04017107, 2017. https://doi.org/10.1061/(ASCE)GM.1943-5622.0001016

[38] A. Grizi, A. Athanasopoulos-Zekkos, and R. Woods, "Ground vibration measurements near impact pile driving," *J. Geotech. Geoenviron.*, p. 04016035, 2016. https://doi.org/10.1061/(ASCE)GT.1943-5606.0001499