

Article

Assessment of Vibration Impacts on Surrounding Buildings Induced by Rock Foundation Construction

Tongxi Zhao ^{1,*}, Daxing Zhou ² and Haifeng Guo ²¹ School of Civil and Hydraulic Engineering, Huazhong University of Science and Technology, Wuhan 430074, China² China Railway Construction Group Co., Ltd., Beijing 100040, China

* Correspondence: tongxi_zhao@hust.edu.cn

Abstract

To address the safety assessment challenges associated with repeated and continuous excavation-induced vibrations in high-rise residential projects founded on hard rock, this study proposes a novel multi-scale dual-control evaluation framework bridging macroscopic ground peak particle velocity (PPV) with microscopic structural principal tensile stress. A geotechnical–structural decoupling approach was adopted. First, a two-dimensional dynamic finite element model of the ground was developed to simulate the propagation and attenuation characteristics of elastic waves under continuous excavation impact loading. Subsequently, the acceleration time histories extracted from the soil–structure interface were applied as base excitations in a three-dimensional structural finite element model to systematically investigate the dynamic response characteristics. The scientific novelty of this research lies in quantitatively decoupling the dynamic sensitivities between primary load-bearing shear walls and secondary non-load-bearing walls, thereby overcoming the inherent blind spots of conventional PPV-only macroscopic assessments. The results indicate that in hard-rock foundations, vibration energy is dominated by vertical attenuation characteristics. Compared with primary load-bearing structures mainly governed by static self-weight effects, secondary non-load-bearing components with lower stiffness exhibit significantly higher dynamic sensitivity and localized vulnerability to continuous impact loading. Parametric analysis further reveals that while the number of operating equipment shows a linear positive correlation with vibration amplitude, the impact frequency dictates the system’s dynamic response. Notably, when the excitation frequency approaches the dynamically sensitive frequency range of the foundation system, a pronounced divergence in response characteristics is observed—manifested as a sharp increase in local structural stress despite a reduction in ground macroscopic vibration intensity. These findings provide a rigorous theoretical foundation and a refined methodology for vibration impact assessment in urban hard-rock foundation construction.



Academic Editor: Tengyuan Zhao

Received: 1 June 2026

Revised: 26 June 2026

Accepted: 3 July 2026

Published: 7 July 2026

Copyright: © 2026 by the authors.

Licensee MDPI, Basel, Switzerland.

This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

Keywords: rock foundation; vibration response; safety assessment; parametric sensitivity analysis

1. Introduction

With the continuous expansion of urban underground space development and high-density construction, the spatial separation between newly constructed projects and existing adjacent buildings has been substantially reduced. Consequently, environmental vibration induced by construction activities has emerged as a critical technical challenge restricting sustainable urban development. Ground vibrations generated by blasting, pile

driving, and mechanical rock excavation may not only cause structural damage to nearby residential buildings and deterioration of the living environment [1–9], but can also propagate over long distances through geological media, thereby interfering with the normal operation of highly sensitive scientific facilities located both on the ground surface and underground [10]. This issue is particularly pronounced in hard-rock foundations such as basalt formations, where the high elastic modulus and low damping characteristics of the rock mass result in slow attenuation and long-range propagation of construction-induced stress waves [11]. As a consequence, the potential impact of construction vibrations on surrounding environments and vibration-sensitive targets is significantly amplified. Against this background, increasingly stringent environmental protection requirements and engineering safety regulations have imposed substantial restrictions on conventional blasting excavation techniques characterized by high vibration intensity. In contrast, low-vibration mechanical rock-breaking methods, represented by hydraulic breakers, have gradually become a preferred solution for hard-rock excavation owing to their reduced environmental disturbance and superior adaptability to complex urban construction conditions [12].

At present, peak particle velocity (PPV) has been widely adopted as a primary indicator for assessing construction-induced vibration risks [2] and has been incorporated into numerous international standards as a recommended vibration control criterion [13–16]. In the field of vibration propagation prediction, Charles H. Dowding and co-workers [17] proposed a classical empirical attenuation model based on field monitoring data, accounting for both geometric spreading and material damping effects. Subsequently, Manoj Khandelwal and T. N. Singh [18], as well as Mohammad Hajihassani and co-workers [19], introduced data-driven approaches, including artificial neural networks, into PPV prediction, significantly improving the accuracy of vibration response estimation under complex engineering conditions. As research focus gradually shifted from predicting site vibration intensity to evaluating its environmental impacts, Wang et al. [7] quantified the propagation effects of excavation-induced vibrations on adjacent underground facilities. Building upon this foundation, Guinchard et al. [8] further developed a refined assessment framework that integrates source characterization, seismic vibration monitoring, and transfer function analysis, enabling a comprehensive evaluation process from vibration source input to target-site response.

In the field of building and foundation dynamic response assessment, research efforts have gradually evolved from macroscopic vibration monitoring toward a more detailed investigation of local structural responses. Ozturk and Coskun [20] derived closed-form solutions for the free vibration of beams resting on elastic foundations with various boundary conditions. Their study systematically quantified the influences of foundation stiffness, axial loading, and support constraints on the natural frequencies, providing a theoretical basis for understanding the dynamic behavior of foundation-supported structures. With respect to structural responses induced by construction activities, Mark Svinkin [21] systematically summarized the dynamic characteristics of construction vibration sources, including pile driving and blasting operations, together with corresponding vibration mitigation measures. Subsequently, Wang and Zhu [1] established an impedance-theory-based prediction model to quantify the propagation characteristics of vibrations generated by mechanical rock excavation in rock foundations within building structures. Furthermore, Wu et al. [22] and Shi et al. [23] revealed key dynamic response mechanisms of buildings subjected to tunnel boring machine (TBM) excavation and tunnel blasting, including stress-wave transmission, elevation amplification, and the whip-lash effect. In addition, for vibrations induced by railway operations, Jing et al. [24] and Zhang et al. [25] investigated the propagation characteristics of long-duration micro-vibrations and the associated floor amplification effects within soil–foundation–structure systems through field monitoring

campaigns. These studies collectively indicate that structural dynamic responses are governed not only by vibration source intensity but also by vibration frequency characteristics, structural dynamic properties, and the complex interactions between the foundation and superstructure [26].

Despite the substantial advances achieved in understanding construction-induced vibration propagation and structural dynamic responses, several critical challenges remain in the refined assessment of vibrations generated by continuous mechanical excavation in hard-rock foundations. First, existing studies have predominantly focused on blasting-induced vibrations or traffic-related microtremors, whereas the propagation and attenuation mechanisms of vibrations generated by the continuous high-frequency impacts of hydraulic breakers have not yet been fully elucidated. Second, current assessment frameworks generally evaluate structural safety based on the overall building response, without adequately accounting for the differences in dynamic characteristics and vibration resistance between load-bearing and non-load-bearing structural components. As a result, local vulnerable zones that may be susceptible to high-frequency vibration effects cannot be accurately identified. Furthermore, under conditions involving the simultaneous operation of multiple construction equipment units, the wave-field interference among vibration sources, as well as local resonance amplification induced by variations in excitation frequency, remains insufficiently investigated. These knowledge gaps limit the development of refined methodologies for the prediction, assessment, and control of construction vibration risks.

To address the aforementioned research gaps, this study investigates a typical high-rise residential project founded on Quaternary basalt formations. A decoupled geotechnical-structural dynamic analysis framework is adopted, in which a two-dimensional ground vibration propagation model is integrated with a three-dimensional structural dynamic response model to characterize the spatial attenuation behavior of vibrations induced by continuous hydraulic-breaker impacts and the corresponding dynamic responses of adjacent buildings. A dual-criterion safety assessment framework is established based on both ground peak particle velocity (PPV) and the maximum principal tensile stress within structural components. Particular emphasis is placed on decoupling the dynamic sensitivities and spatial stress-gradient characteristics of primary load-bearing walls and secondary non-load-bearing walls under combined static and dynamic loading conditions. Furthermore, a series of parametric analyses considering the number of operating hydraulic breakers and impact frequency are conducted to quantitatively investigate the spatial interference and superposition mechanisms of multiple mechanical vibration sources, as well as the nonlinear stress amplification effects associated with local resonance when the excitation frequency approaches the natural frequency of the structure. The findings provide a theoretical basis for the risk assessment and vibration-control design of mechanical excavation activities in hard-rock foundations.

2. Engineering Background and Safety Assessment Standards

2.1. Project Overview

This study is based on a typical multi-story residential project in Hainan, China, as shown in Figure 1. The site strata mainly consist of Quaternary Pleistocene basalt, and the rock mass exhibits good integrity and belongs to the hard rock category. Multiple 16–25-story high-rise buildings with reinforced concrete shear wall structures (supported by raft foundations) are located within the site. Considering the hard rock geological conditions, hydraulic breakers were adopted for mechanical rock excavation during foundation pit construction. Since the construction area is located adjacent to existing buildings (with the nearest building being approximately 25 m from the construction source), the high-frequency impact vibrations generated by hydraulic breakers can easily propagate

outward through the hard bedrock, thereby inducing dynamic responses and even local damage in surrounding structures. Therefore, it is necessary to systematically investigate the propagation characteristics of mechanical construction-induced vibrations and their safety impact mechanisms on adjacent buildings under such typical hard-rock foundation conditions, and to provide a theoretical basis for construction vibration control and safety assessment.



Figure 1. Residential Community Rendering.

2.2. Vibration Source Characteristics Analysis

In hard-rock foundation excavation, the operation of hydraulic breakers exhibits typical transient impact characteristics and presents features such as high-frequency loading, continuous energy input, and macroscopic quasi-periodicity. This continuous mechanical impact can generate strong stress waves within the bedrock. From the perspective of the dynamic mechanism, part of the energy input by the hydraulic breaker is consumed by local plastic crushing of the bedrock, while the remaining part is converted into elastic waves and radiates into the surrounding rock–soil medium. Since this study mainly focuses on the overall dynamic response of building structures in the medium- and far-field regions, the local nonlinear energy dissipation process associated with source-region rock fragmentation can be reasonably neglected, and the mechanical impact on the bedrock can be equivalently represented as a series of periodic pulse dynamic loads applied to ground surface nodes.

To accurately reproduce this excitation characteristic, a typical equivalent mechanical model of the vibration source was established based on the mechanical performance parameters of the actual construction equipment (SANY SHY140 hydraulic breaker; SANY Heavy Industry Co., Ltd., Beijing, China). The peak value of a single impact force was set to 40 kN, and the standard operating frequency was set to 400 bpm (corresponding to an equivalent loading period of 0.15 s). In addition, considering the typical inclined posture of the hydraulic breaker arm during actual excavation, the vector direction of the equivalent nodal load was defined as 45° downward relative to the horizontal plane.

Considering that the vibration characteristics in practical engineering are affected by multiple complex factors, such as equipment operating conditions (e.g., the number of simultaneously operating equipment and impact frequency) and rock mass conditions, a single reference working condition is insufficient to comprehensively reflect the vibration

risk of structures. Therefore, based on the above equivalent model under the reference working condition, a parametric analysis framework was further introduced to systematically investigate the sensitivity characteristics of building structural response and safety under multidimensional variations in vibration source parameters.

2.3. Safety Assessment Criteria

To comprehensively evaluate the influence of rock foundation construction-induced vibrations on surrounding building structures, a dual safety assessment criterion was established in this study from the perspectives of structural response and vibration intensity.

(1) Safety criterion based on structural stress response

The structural damage under vibration essentially depends on whether the internal peak tensile stress exceeds the ultimate tensile strength of the material. Therefore, the maximum principal tensile stress is adopted as the assessment criterion:

$$\sigma_{t,max} \leq [f_t] \quad (1)$$

where $\sigma_{t,max}$ is the maximum principal tensile stress generated in structural components under vibration loading (MPa); $[f_t]$ is the allowable tensile strength of the structural material (MPa).

Considering the significant differences in material properties and load-bearing mechanisms between primary structures (such as reinforced concrete shear walls) and secondary structures (such as masonry infill walls), and in combination with the design characteristics of this project, refined distinctions were made for their corresponding safety limits:

- (a) Primary load-bearing structure: the concrete strength grade ranges from C30 to C40, corresponding to a standard tensile strength value of concrete $f_{tk} = 2.01\sim 2.39$ (MPa) [27].
- (b) Secondary non-load-bearing structure: aerated concrete blocks (A7.5) are adopted, with a mortar strength grade of M5.0, an elastic modulus of $E = 2300$ MPa, and wall thicknesses of 200 mm and 120 mm, respectively. The allowable value f_t is taken as the standard splitting tensile strength of the aerated concrete block wall, i.e., 0.55 MPa [28].

(2) Safety criterion based on vibration intensity

In addition to structural response, vibration intensity itself is also an important indicator for evaluating the influence of construction-induced vibration. Peak particle velocity (PPV) is adopted as the evaluation parameter for vibration intensity, and the vibration safety criterion at the foundation is given as:

$$PPV_{calc} \leq [PPV]_{allow} \quad (2)$$

where PPV_{calc} is the maximum instantaneous vibration velocity of particles at the building foundation extracted from numerical simulation (mm/s); PPV_{allow} is the allowable vibration velocity limit determined according to relevant standards and structural characteristics (mm/s).

The sensitivity of structures to vibration and their damage thresholds are highly dependent on excitation frequency. Low-frequency vibrations (typically below 10 Hz) are more likely to induce coupled resonance with the natural frequencies of buildings. In this study, the fundamental frequency of the hydraulic breaker is approximately 5.83–8.33 Hz (350–500 bpm), which belongs to typical low-frequency mechanical vibration. To scientifically evaluate the vibration risk of the present project, the allowable peak particle velocity (PPV) limits at the foundations of residential buildings specified by mainstream

domestic and international vibration control standards introduced in the Introduction section were comprehensively compared, as shown in Table 1.

Table 1. Natural Frequencies and Effective Mass Participation Ratios of the Structure.

Country	Standard	Frequency Range (Hz)	Allowable PPV Limit for Residential Foundation (mm/s)
China	GB 50868-2013 [29]	1–10	3
Germany	DIN 4150-3:1999	1–10	5
UK	BS 7385-2:1993	4–15	15–20
Switzerland	VSS-SN640-312a	10–60	20

In summary, the comparison indicates that the limit value of 3.0 mm/s specified by the Chinese standard [29] is the most stringent. To implement the principles of engineering worst-case envelope and conservative assessment, the more stringent limit specified by the Chinese standard was ultimately adopted in this study, and $[PPV]_{allow} = 3.0$ mm/s was taken as the baseline threshold for vibration safety assessment.

3. Finite Element Analysis of Vibration Effects of Rock Foundation Construction on Surrounding Buildings

To systematically investigate the vibration impact, a geotechnical–structural decoupling approach was adopted in this study. The overall analytical workflow consists of three sequential stages. First, the physical impact of the hydraulic breaker is mathematically translated into an equivalent dynamic load. Second, a two-dimensional dynamic ground model (Section 3.1) is established to simulate the propagation of elastic waves and extract the acceleration time histories at the target soil–structure interface. Finally, these extracted time histories are applied as base excitations in a three-dimensional structural model (Section 3.2) to evaluate the dynamic responses of different building components. It should be noted that this decoupled assumption intrinsically neglects the feedback effects of structural inertia on the ground response (i.e., radiation damping). As highlighted by recent advanced studies [30], a fully coupled soil-pile-structure interaction (SPSI) framework is essential for accurately capturing energy transfer mechanisms and seismic demands, particularly under large-deformation scenarios or highly nonlinear soil conditions (such as liquefiable deposits). However, the decoupled method is highly appropriate for the current serviceability-level vibration assessment in hard rock, where both the foundation and the structure operate strictly within the linear elastic range with minimal displacements. Furthermore, if a fully coupled framework were considered, the structural radiation damping would dissipate additional energy back into the ground, slightly reducing the structural response. Therefore, by neglecting this feedback mechanism, the decoupled model intentionally yields moderately conservative structural responses, establishing a more rigorous and robust safety envelope for the adjacent buildings.

3.1. Modeling of Ground Vibration Propagation

(1) Finite element analysis of the ground model

To investigate the propagation characteristics of impact waves in hard basalt, a dynamic finite element model was established based on MIDAS GTS NX. The ground conditions are described in Section 2.1. During modeling, the silty clay layer with extremely small thickness was neglected, and the moderately weathered basalt was simplified as a homogeneous linear elastic continuum to characterize its dynamic response under small deformation conditions. The geometric dimensions of the model were set as 150 m × 50 m. To effectively absorb outgoing waves and minimize spurious reflection interference at the

truncated boundaries, standard viscoelastic artificial boundaries (implemented as continuous spring-dashpot systems) were adopted at the lateral sides and the bottom. These boundary elements are formulated based on the dynamic properties of the surrounding rock mass, which is a widely accepted approach in geotechnical dynamic analysis.

Considering that the objective of this study is to evaluate the vibration effects of hydraulic breaker excavation on adjacent residential buildings, the equivalent vibration source was applied at the ground surface, and the nearest building was located approximately 25 m from the source according to the actual engineering layout. To investigate the spatial attenuation characteristics of construction-induced vibrations, a series of monitoring points were arranged at different propagation distances along the ground surface for extracting vibration responses and evaluating the variation in peak particle velocity (PPV) with distance. The resulting numerical model, including the vibration source, building location, monitoring points, and boundary conditions, is shown in Figure 2.

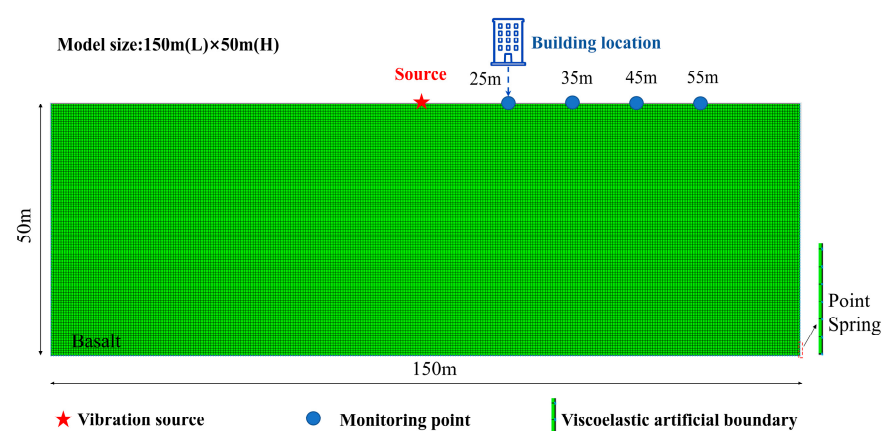


Figure 2. 2D Foundation Model.

The basic dynamic parameters of the rock mass, including unit weight, elastic modulus, and Poisson's ratio, were considered in the model to ensure that the vibration propagation characteristics could be reasonably represented. The detailed parameters are listed in Table 2. Additionally, the fixed damping ratio of the rock mass was set to 2.5% based on the dynamic properties specified in the geotechnical site investigation report for this specific project, ensuring that the baseline model aligns accurately with the actual intact, hard basalt site conditions.

Table 2. Constitutive Model Parameters.

Unit Weight/(kN/m ³)	Elastic Modulus/(kN/m ²)	Poisson's Ratio	Damping Ratio
30	100,000,000	0.2	0.025

In terms of geometric dimension selection, a two-dimensional plane strain model was adopted in this study. It should be acknowledged that stress-wave radiation and geometric attenuation are inherently three-dimensional in reality. For the simulation of point-source vibration, the rationality of this 2D assumption lies in the following aspects: on the one hand, the two-dimensional model essentially treats the vibration source as a line source with infinite out-of-plane extension, which can effectively envelop the worst-case interference condition of multiple hydraulic breakers operating simultaneously along the excavation line; on the other hand, because the two-dimensional model restricts the spatial spreading of waves in the third dimension, the calculated vibration amplitudes in the medium- and

far-field regions are systematically higher than the actual 3D attenuation values. This inherent overestimation has been confirmed through the multi-point validation (comparing simulated and measured responses at 15 m, 25 m, and 35 m) presented in Section 3.3. Therefore, the assessment results derived from this simplified model intentionally constitute a conservative safety envelope. Because the structural integrity is verified against these systematically overestimated vibration levels, it provides an additional and robust safety margin for the adjacent buildings in practical engineering.

(2) Equivalent input of vibration loading and multi-source superposition model

(a) Loading time-history pattern and input validation.

To reproduce the actual mechanical performance, a symmetric triangular pulse was adopted to represent a single impact load, as shown in Figure 3b. While actual contact force-time histories from breaker operations may exhibit more complex, irregular high-frequency oscillations due to local rock fragmentation, the symmetric triangular pulse effectively captures the macroscopic fundamental energy input characteristics (i.e., peak force and effective action duration). The reliability of this equivalent simplified loading is justified by the field validation presented later in Section 3.3, where the simulated ground responses excited by this triangular pulse show a high degree of consistency with the measured field data in both the time domain (amplitude attenuation) and frequency domain (dominant frequencies).

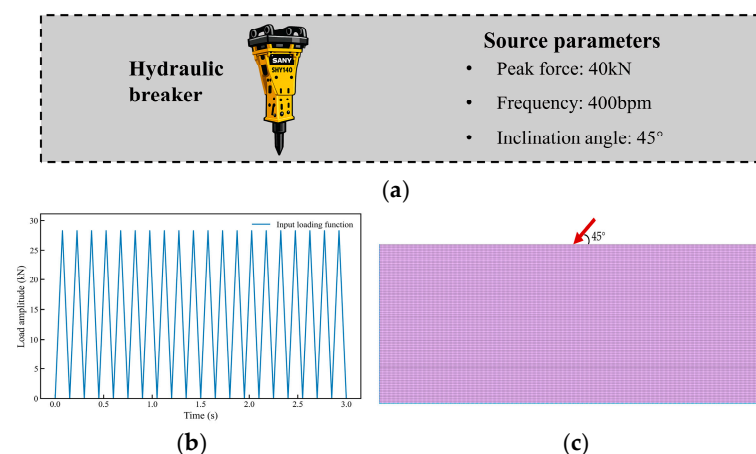


Figure 3. Equivalent vibration source model. (a) Hydraulic breaker and source parameters. (b) Equivalent load time-history function. (c) Location and Direction of Applied Nodal Load.

The resultant time-history load function of a single impact, $F(t)$, can be expressed as:

$$F(t) = \begin{cases} \frac{40}{0.075}t & (0 \leq t < 0.075) \\ 40 - \frac{40}{0.075}(t - 0.075) & (0.075 \leq t \leq 0.15) \end{cases} \quad (3)$$

Combining the excitation frequency of 400 bpm, the duration of a single excitation cycle was set as 0.15 s (with loading/unloading durations of 0.075 s), and the peak value of the resultant force was set as 40 kN. Based on the actual operating posture of the equipment, the load was applied to the ground surface at an inclination angle of 45° downward (Figure 3c), and was orthogonally decomposed into independent horizontal and vertical time histories in the two-dimensional model (with a peak value of approximately 28.3 kN in each direction). Through comparison and validation against field monitoring data (Section 3.3), it was verified that the adopted time-history input and equivalent parameters can reasonably represent the energy diffusion characteristics of wave sources in rock media.

(b) Synchronous superposition and conservative boundary

For the case of multiple equipment operating simultaneously, although the actual physical process involves asynchronous random interference among multiple vibration sources (where phase cancelation may occur), a fully synchronous operation assumption with identical frequency and phase (Synchronous operation) was uniformly adopted in this study based on the principle of safety assessment. This condition enforces the maximum spatial coherent superposition, and the resulting structural dynamic response constitutes the most unfavorable safety envelope for the effects of actual construction activities.

3.2. Finite Element Analysis of Building

To analyze the dynamic response characteristics of building structures under rock foundation construction-induced vibration, the shear wall residential building closest to the construction source (25 m) was selected, and a three-dimensional shell-beam element dynamic model was established using ETABS (with a modal damping ratio of 0.05), as shown in Figure 4.

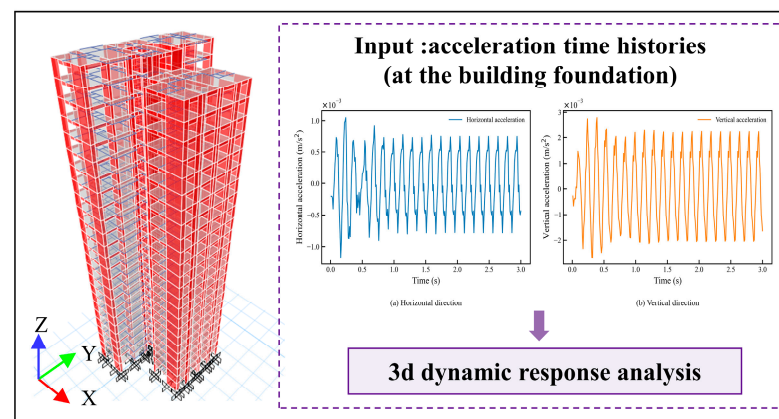


Figure 4. 3D Structural Dynamic Response Model.

In the model, the primary shear walls and floor slabs were simulated using shell elements (Shell), while the frame beams were simulated using beam elements (Beam). The characteristic acceleration time histories obtained from the previously established ground model were used as base excitations, and dynamic time-history analyses were conducted under the conditions of “vibration loading” and “dead load + vibration loading”, providing reliable input for the subsequent stress safety assessment of primary and secondary structural components. (Dead load: a floor dead load of 4 kPa was adopted, including floor finishing and partition wall loads; Live load: 2.0 kPa for residential areas and 2.5 kPa for balconies.).

3.3. Validation of Ground Vibration Model

To verify the rationality and accuracy of the established numerical model based on “equivalent loading–two-dimensional ground wave propagation”, a validation strategy combining “single-point time-history characteristics” and “multi-point spatial attenuation” was adopted, and comparisons with field monitoring data were carried out.

(1) Validation of time-history characteristics at a typical monitoring point

A reference point located 25 m away from the construction source was selected as the benchmark point. The comparison results show (see Figure 5) that the simulated velocity time history exhibits obvious periodic pulse characteristics, and its dominant frequency

is highly consistent with the impact frequency of the hydraulic breaker (400 bpm). In terms of amplitude, the simulated PPV values in the vertical and horizontal directions (0.056 mm/s and 0.022 mm/s) are slightly higher than the measured values (0.048 mm/s and 0.019 mm/s), with the errors controlled within 15–17%, demonstrating the reliability of the equivalent loading approach.

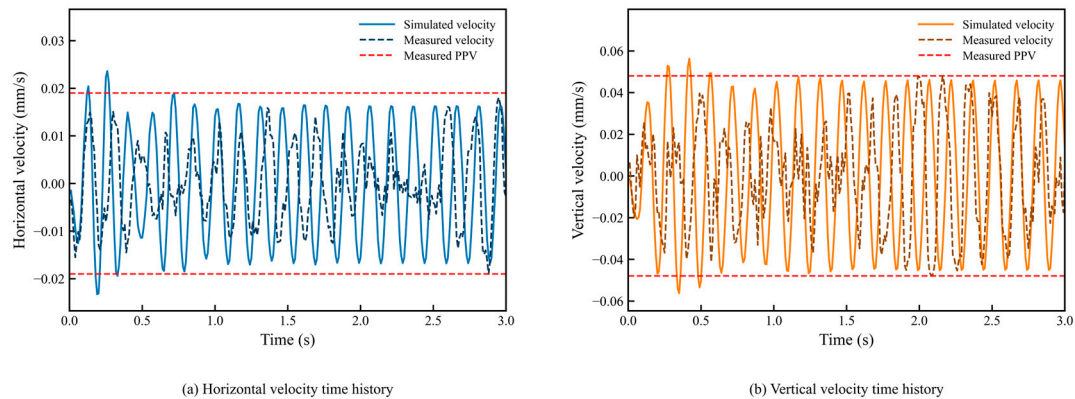


Figure 5. Simulated and measured velocity time histories at 25 m from the vibration source.

The monitoring point located 25 m from the vibration source was selected as the benchmark for model validation. Comparisons between the simulated and measured velocity time histories and amplitude spectra are presented in Figures 5 and 6, respectively. The time-history responses exhibit pronounced periodic impulsive characteristics, and the overall waveform evolution shows good agreement between the simulated and measured results. In terms of peak response, the simulated horizontal and vertical peak particle velocities (PPVs) are 0.022 mm/s and 0.056 mm/s, respectively, while the corresponding measured values are 0.019 mm/s and 0.048 mm/s, resulting in relative errors of 15.8% and 16.7%. The simulated responses are consistently higher than the measured values, indicating a conservative prediction and demonstrating that the equivalent loading model can reasonably reproduce the time-domain characteristics of construction-induced vibrations.

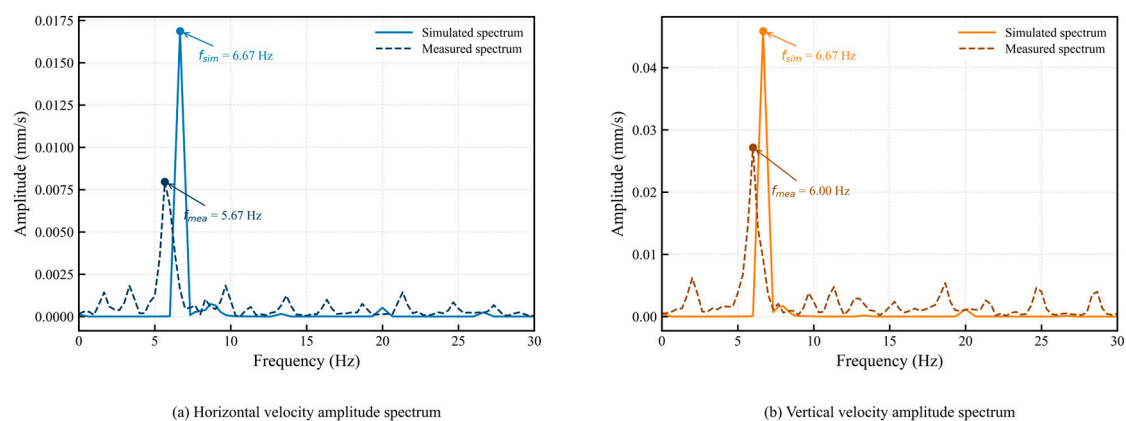


Figure 6. Simulated and measured velocity amplitude spectra at 25 m from the vibration source.

From the frequency-domain perspective, the simulated responses in both horizontal and vertical directions exhibit a dominant frequency of 6.67 Hz, which agrees well with the theoretical excitation frequency corresponding to the breaker impact rate (400 bpm). The measured dominant frequencies are 5.67 Hz and 6.00 Hz, respectively, which are slightly lower than the simulated values; however, the vibration energy remains primarily concentrated within the 5–7 Hz frequency band. In addition, several secondary spectral peaks

are observed in the measured spectra, indicating a certain degree of frequency dispersion. This phenomenon can be attributed to fluctuations in excitation forces during construction, wave scattering attenuation during propagation, and the inherent heterogeneity of the ground medium. Although slight deviations exist in the dominant frequencies, both the simulated and measured results indicate that the vibration energy is concentrated within a comparable frequency range.

Overall, the comparison of the time-domain waveforms and dominant frequency characteristics demonstrates that the proposed vibration analysis model possesses satisfactory engineering applicability and can be reliably employed for subsequent parametric sensitivity analyses and vibration impact assessments of adjacent structures.

(2) Multi-point validation of spatial attenuation trends

After confirming the rationality of the single-point waveform characteristics, multiple monitoring points at 15 m, 25 m, and 35 m were selected to analyze the spatial propagation characteristics of waves. The relative errors between the calculated PPV values and the measured values at each monitoring point range from 13.2% to 21.4%. The comparison results are shown in Figure 7. Significant physical characteristics indicate that the simulated values at all monitoring points are consistently greater than the measured values, and the error tends to increase with increasing distance. This phenomenon also verifies the theory described in Section 3.1, namely that the two-dimensional model overestimates the far-field response due to its restriction on out-of-plane geometric spreading, thereby providing a conservative safety envelope for engineering safety assessment.

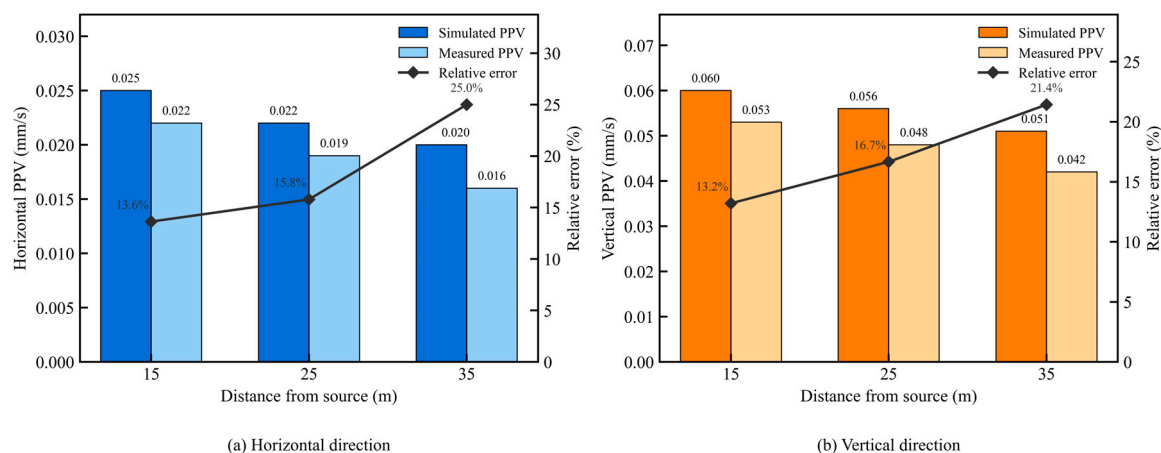


Figure 7. Numerical Model Validation under Multiple Monitoring Points.

In summary, the numerical simulation results not only accurately capture the time-domain characteristics and spatial attenuation patterns of impact waves, but also provide an appropriate safety margin for surrounding buildings while ensuring the accuracy of the mechanical mechanisms, demonstrating a certain degree of engineering applicability.

4. Vibration Propagation, Structural Response, and Safety Assessment

4.1. Vibration Attenuation Characteristics and Safety Assessment in Hard-Rock Foundations

Based on the two-dimensional ground model, the horizontal and vertical peak particle velocities (PPV) at surface monitoring points located at different horizontal distances (5–45 m) from a single hydraulic breaker were extracted. To characterize the attenuation characteristics of vibrations in different directions with propagation distance, a power function model and an exponential function model were adopted to fit the horizontal and vertical PPV values, respectively. The horizontal PPV was fitted using a power-law

attenuation form under logarithmic coordinates, while the vertical PPV was fitted using an exponential attenuation form under semi-logarithmic coordinates. As shown in Figure 8, both the horizontal and vertical PPV values gradually decrease with increasing propagation distance. However, at all monitoring points, the vertical PPV is significantly greater than the horizontal PPV, approximately 2–2.5 times that of the latter, indicating that the vibration response in hard-rock foundations under mechanical impact loading is dominated by the vertical propagation component.

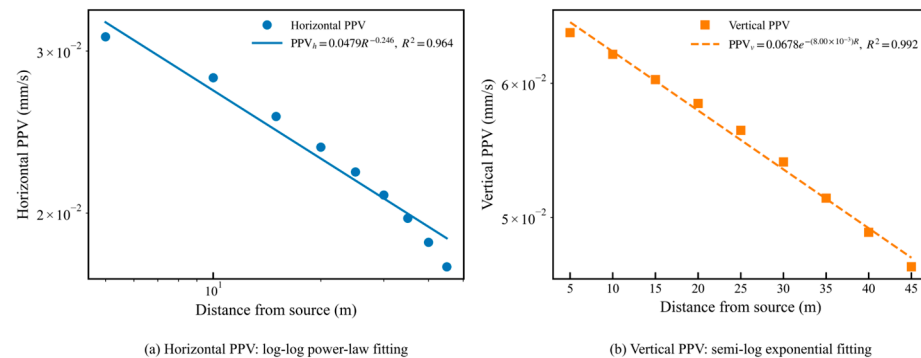


Figure 8. Attenuation Characteristics of Horizontal and Vertical PPV with Propagation Distance (PPV_h —Peak particle velocity in horizontal direction; PPV_v —Peak particle velocity in vertical direction; R —Propagation distance from source; The horizontal follows a power-law attenuation: $PPV_h = k \cdot R^{-n}$; The vertical PPV follows an exponential attenuation: $PPV_v = PPV_0 \cdot e^{-\alpha R}$).

To investigate the attenuation characteristics of hydraulic breaker-induced vibrations in rock foundations, differentiated mathematical fitting methods were adopted for the two directional datasets because the dissipation mechanisms of different wave types in the two-dimensional ground model are fundamentally different.

- (1) Horizontal vibration is dominated by body waves and exhibits a significant in-plane geometric spreading effect; therefore, a power function model was adopted for fitting:

$$PPV_h = k \cdot R^{-n} \quad (4)$$

where k is the attenuation coefficient, R is the propagation distance, and n is the attenuation exponent.

The fitted function is expressed as follows (with a coefficient of determination of 0.964):

$$PPV_h = 0.0479 \cdot R^{-0.246} \quad (5)$$

- (2) Vertical vibration is mainly governed by surface waves (Rayleigh waves). Under the assumption of two-dimensional plane strain, surface waves lack out-of-plane geometric spreading space for energy dissipation, and their attenuation is almost completely dominated by material damping. Therefore, an exponential function model was adopted for fitting:

$$PPV_v = PPV_0 \cdot e^{-\alpha R} \quad (6)$$

where PPV_0 is the equivalent vibration source energy (reflecting the initial energy level input into the foundation by a single impact of the hydraulic breaker), R is the propagation distance, and α is the material damping absorption coefficient (representing the capability of the rock medium to dissipate elastic wave energy through internal friction).

The fitted function is expressed as follows (with a coefficient of determination of 0.992):

$$PPV_v = 0.06784e^{-0.008R} \quad (7)$$

The fitted attenuation models in different directions indicate that, under the strong impact loading of hydraulic breakers, horizontal vibration in hard-rock foundations undergoes significant spatial geometric spreading with wavefront propagation, exhibiting a typical power-law attenuation pattern. In contrast, due to the limitation of geometric dissipation, the energy attenuation of vertical vibration is almost completely dominated by material damping. It can be observed that, because the high-modulus and dense hard basalt exhibits very weak internal absorption of elastic waves, this difference in mechanism—where horizontal vibration is governed by geometric spreading and vertical vibration is governed by low-damping dissipation—allows vertical vibration to maintain a relatively high energy density even in medium- and far-field regions. Based on the principle of engineering worst-case envelope assessment, the vertical PPV was established as the core control index in this study.

In summary, at the boundary of the adjacent building located 25 m away, the calculated vertical PPV is 0.056 mm/s. This value is far below the low-frequency vibration control threshold (3.0 mm/s) determined in Section 2.3. Therefore, in terms of vibration intensity, the current construction condition will not cause damage to the overall building structure, and the site impact remains within a safe range.

4.2. Stress Response and Safety Assessment of Structural Walls

To analyze the influence of construction vibration input on the stress response of structural walls, the most unfavorable acceleration time history at the ground surface located 25 m away (see Figure 9, exhibiting pulse-type characteristics, with the vertical amplitude being significantly greater than the horizontal amplitude) was extracted and applied to the base of the three-dimensional structural model. The combination condition of “1.0 dead load + 1.0 vibration loading” was considered, and the maximum principal tensile stress of walls throughout the entire structure was evaluated.

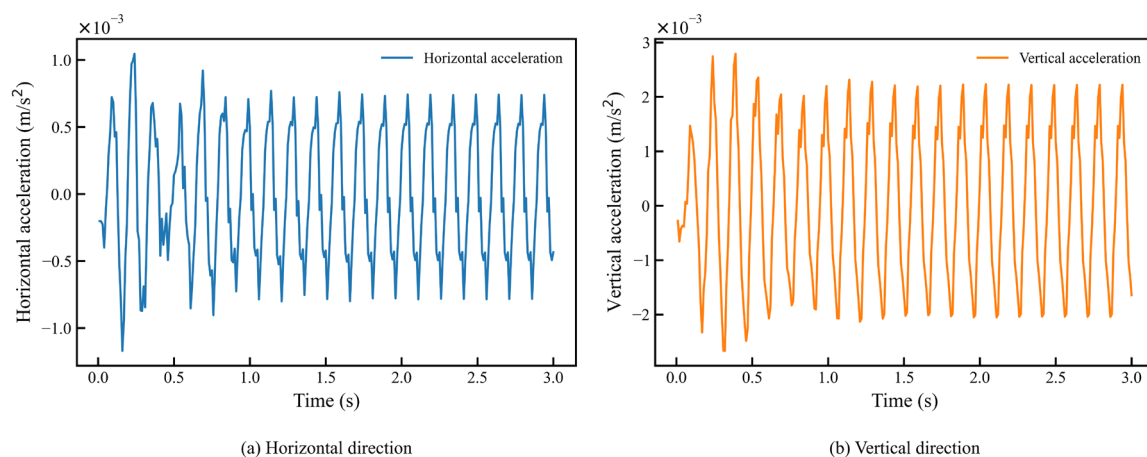


Figure 9. Acceleration Time–History Curves at the 25 m Monitoring Point.

(1) Stress condition and safety assessment of primary structural walls

The calculation results indicate that the tensile stress of the primary load-bearing shear walls is mainly concentrated at the bottom wall limbs (see Figure 10), and the maximum tensile stress is only 0.87 MPa. This value is mainly induced by the self-weight dead load and remains far below the standard tensile strength of concrete (2.01–2.39 MPa). This

indicates that the primary structural framework is subjected to a uniformly distributed stress state and remains in a fully elastic working condition, with no risk of cracking.

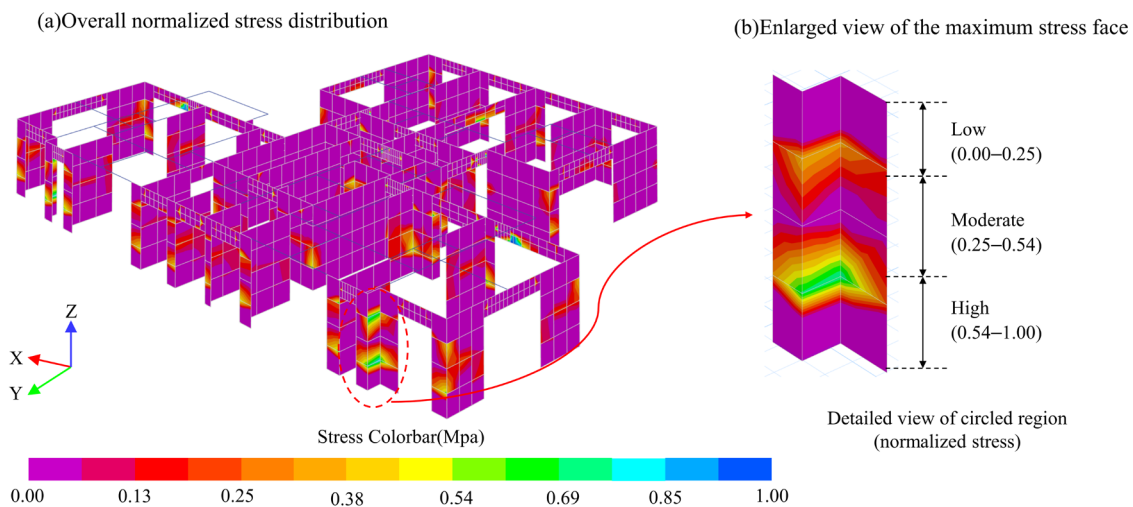


Figure 10. Tensile Stress Contour of the Main Structural Wall at a Typical Floor.

(2) Stress condition and safety assessment of secondary structural walls

For secondary infill walls with relatively weak tensile resistance, local stress concentration is likely to occur at the wall–frame connection interface, while the maximum principal tensile stress forms a continuous tensile stress concentration zone along the middle part of the wall, with a peak value reaching 0.017 MPa (see Figure 11). Although these components have relatively low stiffness and are more susceptible to excitation effects, their maximum principal tensile stress remains far below the standard splitting tensile strength of aerated concrete blocks (0.55 MPa), accounting for only approximately 3.1% of the allowable value, thus satisfying the crack resistance requirement.

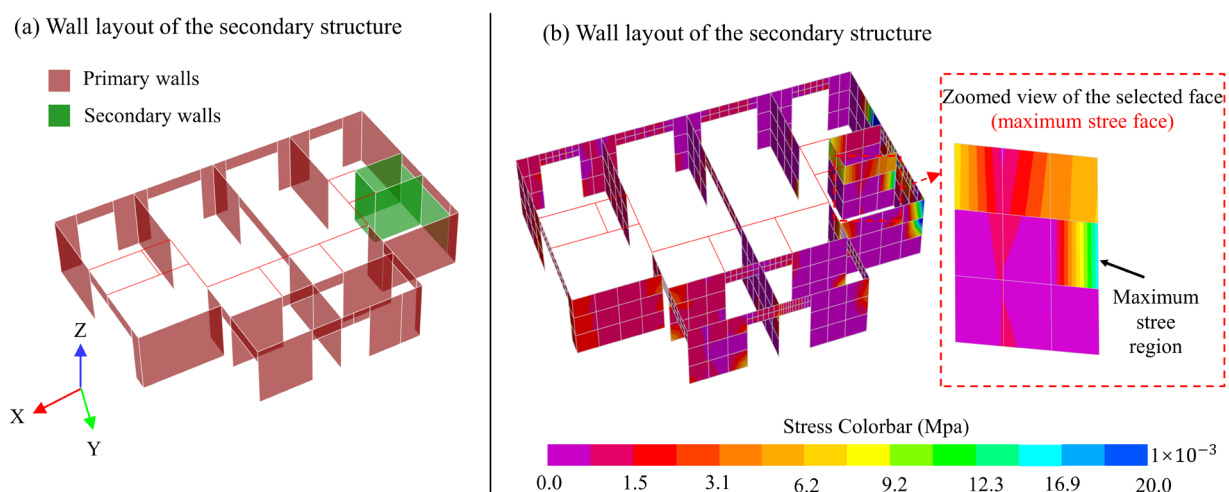


Figure 11. Tensile Stress Contours of the Secondary Structural Wall on a Typical Floor.

4.3. Comparative Dynamic Response of Primary and Secondary Structural Walls

To investigate the influence mechanism of construction-induced vibration on components with different structural characteristics, the tensile stress data of primary and secondary structural walls within a distance range of 5–45 m from the vibration source were extracted in this section. By introducing two loading conditions, namely “vibration only” and “dead load + vibration”, for comparison (see Figure 12), the overall structural

safety was verified and the differences in dynamic sensitivity between the two types of walls were revealed.

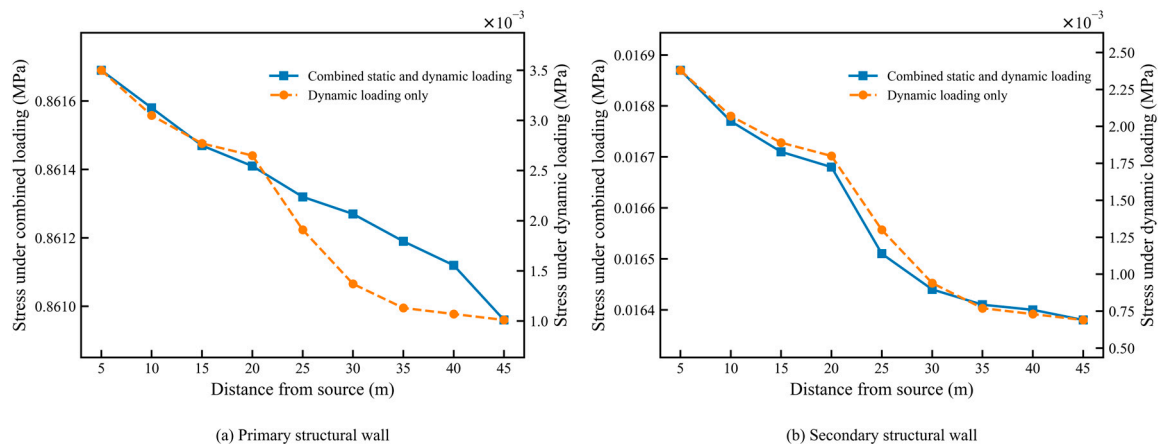


Figure 12. Variation in wall stress with distance under different loading conditions.

(1) Crack resistance safety assessment of primary and secondary structural walls

The calculation results indicate that under the most unfavorable “dead load + vibration” loading condition, no structural damage occurred within all investigated distances (5–45 m). Among them, the peak total tensile stress of the primary shear walls is approximately 0.86 MPa, which is far lower than the standard tensile strength of concrete (2.01 MPa); the peak tensile stress of the secondary infill walls is approximately 0.017 MPa, which is also strictly controlled within the tensile strength limit of masonry (0.06 MPa). The above magnitude comparison clearly demonstrates that under the current level of mechanical excavation-induced vibration, both the primary load-bearing structures and the secondary non-load-bearing structures remain in a fully elastic working state, far from reaching their respective tensile failure thresholds. This verified damage-free state confirms that the linear elastic constitutive models adopted in this study are sufficient and reliable for the current serviceability-level assessment.

(2) Decoupling of dynamic and static effects and mechanism of sensitivity differences

Although both the primary and secondary structures remain within the safe range in terms of absolute magnitude, significant differences exist in their dynamic response mechanisms.

By decoupling the “vibration only” condition, it was found that the pure dynamic additional stresses of both types of walls exhibit a substantial attenuation of approximately 70% with increasing distance, indicating that the vibration waves in the foundation have similar input and dissipation trends within the structures. However, under the actual “dead load + vibration” combined condition, their spatial evolution characteristics show considerable differences:

For primary structural walls, due to the relatively large static self-weight load, the dynamic additional stress only constitutes a minor disturbance, and the variation rate of total stress with distance is less than 0.1%, indicating that the internal force state is absolutely dominated by self-weight. In contrast, for secondary structural walls, the static stress baseline is very low, and the same level of dynamic disturbance causes the spatial variation rate of total tensile stress to reach 3% (approximately 30 times that of the primary structure). This comparison quantitatively reveals that secondary structures exhibit higher dynamic sensitivity to the propagation and evolution of vibration waves compared with primary structures.

In summary, secondary structural walls not only exhibit attenuation characteristics similar to those of primary structural walls under vibration loading, but also maintain a certain response capability to changes in vibration input under combined loading conditions, indicating that they are more sensitive to construction-induced vibration and should receive particular attention in engineering practice.

5. Parametric Sensitivity Analysis

To further reveal the controlling mechanisms of construction parameter variations on the wave field in hard-rock foundations and the dynamic responses of surrounding buildings, a characteristic observation point located 25 m away from the vibration source (at the boundary of the adjacent building) was selected in this section. Taking the condition of a single operating hydraulic breaker with an impact frequency of 400 bpm as the reference case, a systematic parametric sensitivity analysis was conducted to evaluate the influence of various parameters on structural safety.

The selection of key analysis parameters and their corresponding ranges was strictly based on actual construction scenarios and the physical performance specifications of the equipment:

- (1) Operating scale: Considering the common multi-machine cluster operation adopted in hard-rock foundation pit excavation, the number of hydraulic breakers operating synchronously was set to 1–6 units, with the objective of quantifying the spatial coherent superposition effect of multiple vibration sources and identifying the most unfavorable safety boundary.
- (2) Dynamic input: Based on the rated operating performance of the SANY SHY140 hydraulic breaker used in this project, the variation range of impact frequency was defined as 350–500 bpm, in order to investigate the influence of shifts in the actual excitation spectrum on the frequency-domain coupling and resonance amplification mechanisms of structural response.

Through the decoupled analysis of the above parameters with clear engineering significance, this study aims to quantitatively evaluate the driving mechanisms and relative influence of each parameter on site vibration intensity and the safety of structural components.

5.1. Influence of the Number of Operating Equipment on Vibration Intensity and Structural Stress

(1) Vibration intensity (PPV):

With the increase in the number of operating equipment, both horizontal and vertical PPV exhibit a significant linear increase (see Figure 13). Among them, the vertical PPV increases from 0.056 mm/s to 0.338 mm/s, indicating that multi-equipment operation induces spatial coherent superposition of vibration energy. Through linear fitting of the vertical PPV, $PPV = 0.0563 \cdot N$ (where N is the number of operating equipment), and extrapolation based on the code limit value (3.0 mm/s), the critical number of operating equipment is predicted to be approximately 54. Considering the limitations of the working space in elongated foundation pits and the typical conditions encountered in practical construction, such a scale of equipment deployment is not realistic in engineering practice. This confirms that the multi-machine coordinated rock-breaking mode currently adopted in this project (≤ 6 units).

The stresses of both types of walls also exhibit a linear increase with the increase in the number of operating equipment (see Figure 14), but significant differences in sensitivity are observed. The stress variation rate of primary structural walls is less than 0.5%, indicating that their stress state is absolutely dominated by self-weight; in contrast, due to the relatively low stiffness and low stress baseline, the relative stress variation rate of secondary

structural walls reaches 5%, exhibiting higher sensitivity to the linear superposition of vibration energy.

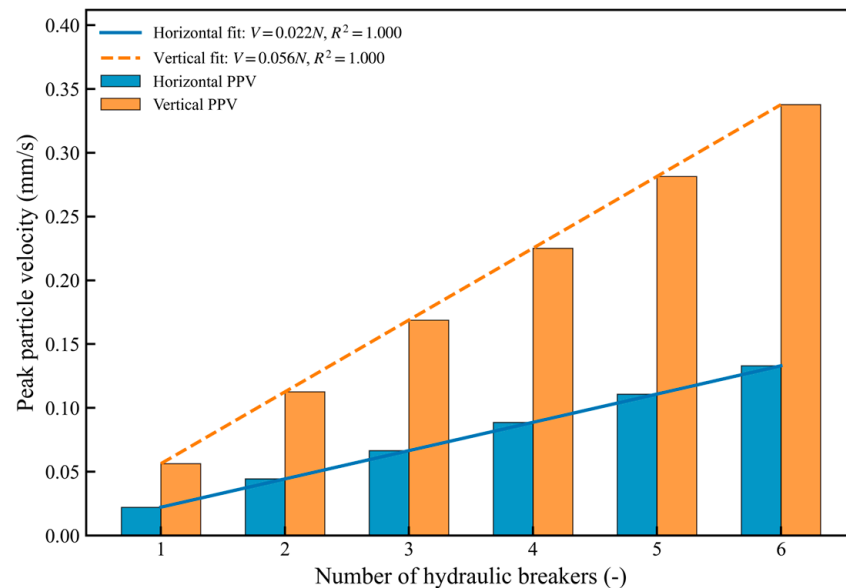


Figure 13. PPV under Different Operating Numbers in a Typical Condition.

(2) Structural stress response:

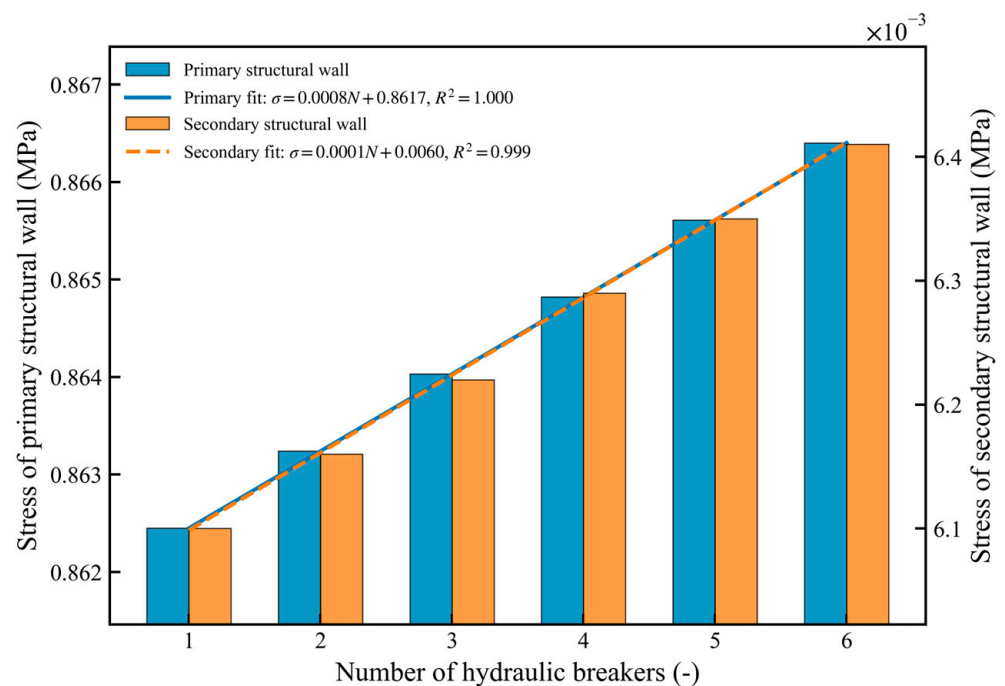


Figure 14. Stress Responses of Main and Secondary Structural Walls under Different Operating Numbers in a Typical Condition.

5.2. Influence of Impact Frequency on Vibration Intensity and Structural Stress

(1) Vibration intensity (PPV):

The influence of frequency variation on PPV exhibits significant nonlinear and directional differences (see Figure 15). The horizontal PPV shows an increasing trend with increasing frequency (increasing from 0.015 mm/s to 0.102 mm/s), whereas the vertical PPV reaches a peak value (0.136 mm/s) at 450 bpm and then decreases at 500 bpm.

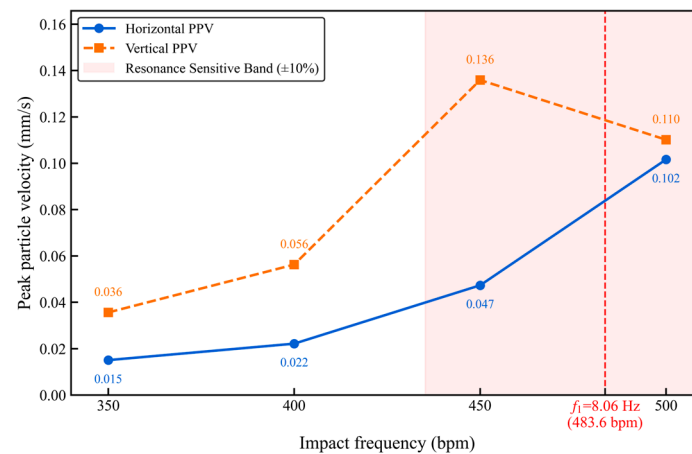


Figure 15. PPV under Different Impact Frequencies in a Typical Condition.

Combined with Table 3, the observed differences are strongly associated with the modal characteristics of the hard-rock foundation system. The first-order mode (8.06 Hz/484 bpm) mainly exhibits vertical vibration participation, whereas the second-order mode (9.06 Hz/543 bpm) mainly exhibits horizontal vibration participation. Therefore, within the current impact frequency range, the vertical excitation frequency gradually approaches the first-order dynamic sensitive frequency band, while the horizontal excitation frequency has not yet entered its primary sensitive range, resulting in different variation trends of PPV in the two directions. Although 500 bpm is theoretically closer to the first-order modal frequency, the vertical PPV reaches its peak at 450 bpm and then decreases. This indicates that the dynamic response of hard-rock foundations is jointly influenced by material damping, wave propagation characteristics, and boundary conditions, and the vibration amplification does not occur only at a single frequency point but exhibits relatively high sensitivity within a certain frequency range. Meanwhile, under the 450 bpm condition, the relatively longer impact interval allows more sufficient propagation and reflection of stress waves, making it easier to generate larger instantaneous peak values. In contrast, under the 500 bpm condition, the shortened impact interval enhances wave phase interference, resulting in a reduction in the time-domain PPV peak value.

Table 3. Natural Frequencies and Effective Mass Participation Ratios of the Hard-Rock Foundation System.

Mode No.	Frequency (Hz)	Effective Mass Ratio (X) (%)	Effective Mass Ratio (Y) (%)
1	8.06	0	91.26
2	9.06	87.53	0
3	12.9	11.32	0
4	18.05	0	8.09
5	22.52	0	0.25
6	26	0.67	0
7	35.5	0	0.28
8	39.4	0.14	0
9	39.8	0.23	0
10	48.2	0	0.02

(2) Structural stress response:

The wall stress exhibits obvious stage-wise characteristics with increasing frequency: it increases gradually within the range of 350–450 bpm, but shows an abnormally sharp increase within the range of 450–500 bpm (see Figure 16).

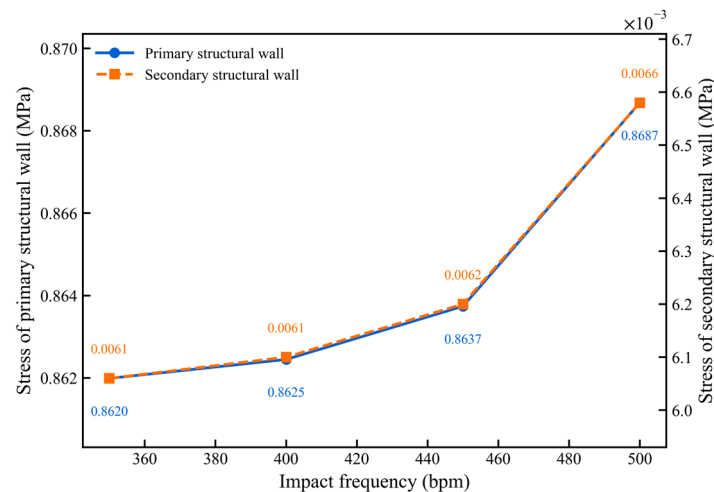


Figure 16. Stress Responses of Main and Secondary Structural Walls under Different Impact Frequencies in a Typical Condition.

Unlike the decrease in PPV, the wall stress continues to increase and reaches its peak at 500 bpm. This divergence indicates that the stress response is not completely synchronized with changes in vibration amplitude, as it is controlled not only by the macroscopic vibration amplitude but is also closely related to the dynamic transmission characteristics of the ground–structure system. As the impact frequency gradually approaches the dynamically sensitive frequency range of the hard-rock foundation system, the vibration input transmitted to the building foundation is amplified, thereby enhancing the stress response of upper structural components. Therefore, even though the ground-surface PPV decreases under the 500 bpm condition due to wave interference effects, the internal structural stress may continue to increase.

This result indicates that the peak value of ground-surface PPV cannot fully reflect the internal stress state of structures. Relying solely on PPV for safety assessment may underestimate the dynamic risk of local structural components; therefore, it is necessary to conduct comprehensive safety assessments in combination with structural stress indicators.

6. Conclusions

For the influence of mechanical excavation in hard-rock foundations on surrounding high-rise buildings, this study carried out a systematic investigation from site attenuation characteristics to structural component responses. The main conclusions are as follows:

- (1) According to the engineering characteristics of hard-rock foundations and the high-frequency impact characteristics of hydraulic breakers, a dual safety assessment framework based on peak particle velocity (PPV) and maximum principal tensile stress of structural components was established. Differentiated safety assessment criteria and corresponding limit values were further defined for primary load-bearing structures and secondary non-load-bearing structures.
- (2) The vibration attenuation characteristics of hard-rock foundations exhibit significant directional differences, with the vertical component being dominant and showing a relatively slower attenuation rate. The decoupling analysis of dynamic and static loading confirms that the internal force state of the primary structure is absolutely dominated by self-weight (stress variation rate < 0.1%), whereas the dynamic sensitivity of secondary structural walls is approximately 30 times that of the primary structure due to their lower stress baseline and lower stiffness, indicating that particular attention should be paid to such components.

- (3) Through parametric sensitivity analysis of construction parameters, it was found that the number of operating equipment controls the energy input level of vibration, and both vibration intensity and structural stress increase approximately linearly with increasing equipment quantity. In contrast, impact frequency significantly affects the dynamic response characteristics of the ground–structure system, resulting in a divergence between ground-surface PPV (reaching a peak at 450 bpm) and structural stress (continuing to increase at 500 bpm). This indicates that ground vibration intensity alone cannot fully reflect the internal stress state of structures. Therefore, in practical construction, not only should the scale of mechanical operation be restricted, but construction frequencies close to the dynamically sensitive frequency range of the hard-rock foundation system (450–500 bpm) should also be avoided as much as possible to reduce the risk of enhanced dynamic responses in local structural components.

In summary, the primary scientific gain of this research lies in advancing the paradigm of construction vibration assessment from conventional macroscopic “PPV-only” evaluations to a refined, multi-scale “geotechnical-structural decoupled” framework. By quantitatively demonstrating that local structural stress responses can severely diverge from ground surface vibration intensities—particularly when excitation approaches the foundation’s dynamically sensitive frequency bands—this study overcomes the inherent blind spots of traditional assessment criteria. Furthermore, the explicit decoupling of dynamic sensitivities between primary load-bearing and secondary non-load-bearing components provides a robust theoretical basis for identifying highly localized, non-obvious structural vulnerabilities. Ultimately, these findings contribute a rigorous analytical methodology for the sustainable and safe development of high-density urban spaces in complex hard-rock geological settings.

Although this study systematically evaluated the vibration responses of surrounding buildings induced by mechanical excavation in hard-rock foundations and innovatively proposed a dual-control framework based on macroscopic PPV and microscopic tensile stress, several limitations still exist due to computational scale and physical modeling assumptions:

- (1) The two-dimensional plane model and the assumption of a homogeneous continuous rock mass cannot fully represent the three-dimensional spatial propagation and dissipation mechanisms of high-frequency stress waves in naturally fractured rock masses.
- (2) The assumption of fully synchronous excitation does not consider the complex wave-field interference effects caused by asynchronous operation of multiple machines in practical engineering. In reality, phase differences between operating equipment may significantly alter interference patterns, often leading to partial phase cancelation and reduced overall vibration intensity. While our current synchronous assumption effectively establishes a conservative safety envelope, future studies should incorporate sensitivity analyses considering random asynchronous loading scenarios to provide a more precise probabilistic assessment.
- (3) The current assessment is limited to a typical reinforced concrete shear wall structure.

Therefore, future research will focus on developing a more refined three-dimensional dynamic coupling model incorporating multi-source asynchronous excitation, fractured heterogeneous rock masses, and complex building structures. Particular attention will be paid to investigating the influence mechanism of random phase differences among multiple vibration sources on far-field vibration intensity, as well as the differences in dynamic sensitivity among various structural systems, thereby providing a more universally

applicable safety-control theory for mechanical rock-breaking construction under complex urban geological conditions.

Author Contributions: Conceptualization, T.Z. and D.Z.; Methodology, D.Z. and H.G.; Software, H.G.; Validation, H.G.; Formal analysis, T.Z.; Investigation, H.G.; Resources, D.Z.; Data curation, T.Z.; Writing—original draft, T.Z.; Writing—review and editing, D.Z. and H.G.; Visualization, T.Z.; Supervision, D.Z. and H.G.; Funding acquisition, D.Z. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by The National Key R&D Program of China, grant number 2023YFC3009300.

Data Availability Statement: Data is contained within the article.

Acknowledgments: The authors gratefully acknowledge all colleagues and collaborators who provided valuable assistance in data collection, numerical modeling, result analysis, and manuscript preparation.

Conflicts of Interest: Authors Daxing Zhou and Haifeng Guo were employed by the company China Railway Construction Group Co., Ltd. The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. Wang, S.; Zhu, S. Vibration Impact of Rock Excavation on Nearby Sensitive Buildings: An Assessment Framework. *Soil Dyn. Earthq. Eng.* **2022**, *163*, 107508. [CrossRef]
2. Ainalis, D.; Kaufmann, O.; Tshibangu, J.-P.; Verlinden, O.; Kouroussis, G. Modelling the Source of Blasting for the Numerical Simulation of Blast-Induced Ground Vibrations: A Review. *Rock Mech. Rock Eng.* **2017**, *50*, 171–193. [CrossRef]
3. Wang, S.; Zhu, S. Global Vibration Intensity Assessment Based on Vibration Source Localization on Construction Sites: Application to Vibratory Sheet Piling. *Appl. Sci.* **2022**, *12*, 1946. [CrossRef]
4. Zou, C.; Zhu, R.; Tao, Z.; Ouyang, D.; Chen, Y. Evaluation of Building Construction-Induced Noise and Vibration Impact on Residents. *Sustainability* **2020**, *12*, 1579. [CrossRef]
5. Colaço, A.; Ferreira, M.A.; Costa, P.A. Empirical, Experimental and Numerical Prediction of Ground-Borne Vibrations Induced by Impact Pile Driving. *Vibration* **2022**, *5*, 4. [CrossRef]
6. Longinow, A.; Mohammadi, J. Effects of Vibrations on Structures: Overview and Case Studies. *Pract. Period. Struct. Des. Constr.* **2022**, *27*, 04022049. [CrossRef]
7. Wang, S.; Zhu, S.; Yuen, P.L. Assessment of Ground-Borne Vibration Impact on Nearby Underground Facilities Induced by Ground Surface Excavation. *J. Constr. Eng. Manag.* **2021**, *147*, 04021071. [CrossRef]
8. Shioi, A.; Otake, Y.; Yoshida, I.; Muramatsu, S.; Ohno, S. Data-driven approximation of geotechnical dynamics to an equivalent single-degree-of-freedom vibration system based on dynamic mode decomposition. *Georisk Assess. Manag. Risk Eng. Syst. Geohazards* **2023**, *17*, 77–97.
9. Lloret-Cabot, M.; Zhang, K.; Zhang, W.; Kourdey, A.; Hicks, M.A. Quantifying the effects of vibro-compaction on soil heterogeneity and geotechnical uncertainty. *Georisk Assess. Manag. Risk Eng. Syst. Geohazards* **2026**, *20*, 41–61.
10. Guinchart, M.; Cabon, M.; Charrondière, C.; Develle, K.; Fessia, P.; Lacny, L.; Osborne, J.; Scislo, L.; Wenninger, J. Investigation and Estimation of the LHC Magnet Vibrations Induced by HL-LHC Civil Engineering Activities. In Proceedings of the 9th International Particle Accelerator Conference (IPAC'18), Vancouver, BC, Canada, 29 April–4 May 2018; pp. 2568–2571. [CrossRef]
11. Persson, P.-A.; Holmberg, R.; Lee, J. *Rock Blasting and Explosives Engineering*; CRC Press: Boca Raton, FL, USA, 1994.
12. Leggieri, V.; di Lernia, A.; Elia, G.; Raffaele, D.; Uva, G. Vibrations Induced by Mechanical Rock Excavation on RC Buildings in an Urban Area. *Buildings* **2021**, *11*, 15. [CrossRef]
13. SN640-312a; Effet Des Ébranlements Sur Les Constructions. Schweizerische Normen-Vereinigung: Zurich, Switzerland, 1992.
14. BS 7385-2; Evaluation and Measurement for Vibration in Building: Part 2: Guide to Damage Levels from Ground Borne Vibration. British Standard: London, UK, 1993.
15. Schulz, D.L.; Siskind, D.E.; Stagg, M.S.; Wiegand, J.E. Surface Mine Blasting Near Pressurized Transmission Pipelines. 1994. Available online: <https://stacks.cdc.gov/view/cdc/10251> (accessed on 31 May 2026).
16. DIN 4150-3; Part 3: Effects of Vibration on Structures. DIN Germany Institute: Berlin, Germany, 1999.
17. Dowding, C.H. *Construction Vibrations*; Prentice Hall Inc.: Eaglewood Cliffs, NJ, USA, 1996.

18. Khandelwal, M.; Singh, T.N. Evaluation of Blast-Induced Ground Vibration Predictors. *Soil Dyn. Earthq. Eng.* **2007**, *27*, 116–125. [[CrossRef](#)]
19. Hajihassani, M.; Jahed Armaghani, D.; Monjezi, M.; Mohamad, E.T.; Marto, A. Blast-Induced Air and Ground Vibration Prediction: A Particle Swarm Optimization-Based Artificial Neural Network Approach. *Environ. Earth Sci.* **2015**, *74*, 2799–2817. [[CrossRef](#)]
20. Ozturk, B.; Coskun, S.B. Analytical Solution for Free Vibration Analysis of Beam on Elastic Foundation with Different Support Conditions. *Math. Probl. Eng.* **2013**, *2013*, 470927. [[CrossRef](#)]
21. Svinkin, M.R. Minimizing Construction Vibration Effects. *Pract. Period. Struct. Des. Constr.* **2004**, *9*, 108–115. [[CrossRef](#)]
22. Wu, K.; Zheng, Y.; Li, S.; Sun, J.; Han, Y.; Hao, D. Vibration Response Law of Existing Buildings Affected by Subway Tunnel Boring Machine Excavation. *Tunn. Undergr. Space Technol.* **2022**, *120*, 104318. [[CrossRef](#)]
23. Shi, H.; Jiang, N.; Zhou, C.; Zhnag, Y.; Yao, Y.; Zhou, W.; Cai, Z. Safety Assessment of Ancient Buddhist Pagoda Induced by Underpass Metro Tunnel Blasting Vibration. *Eng. Fail. Anal.* **2023**, *145*, 107051. [[CrossRef](#)]
24. Jing, M.; Lu, F.; Chen, Y.; Li, Y.; Gao, S.; Zhang, R. Research on the Vibration Response and Control Technologies for Buildings above the Metro Depot. *J. Build. Eng.* **2025**, *109*, 112908. [[CrossRef](#)]
25. Zhang, Q.; Bai, W.; Dai, J.; Shao, Z.; Yue, J. Implications of Evaluation Algorithms and Added-Structure Effect: Monitoring of Train-Induced Vibration on a Subway-Adjacent Building under Construction. *J. Build. Eng.* **2025**, *110*, 112957. [[CrossRef](#)]
26. Yan, P.; Tian, J.; Zhang, Y.; Hao, L. Study on the Vibration Effects of Brick–Concrete Structures Induced by Blasting in Open-Pit Mines. *Buildings* **2025**, *15*, 2954.
27. GB 50010–2010; Code for Design of Concrete Structures. China Architecture & Building Press: Beijing, China, 2010.
28. JGJ/T 17–2020; Technical Standard for Application of Autoclaved Aerated Concrete Product. China Architecture & Building Press: Beijing, China, 2020.
29. GB 50868–2013; Standard for Allowable Vibration of Construction Projects. China Planning Press: Beijing, China, 2013.
30. Ranjbar, F.; Asgari, A.; Bagheri, M.; Bengar, H.A. Insights into the Mechanisms and Seismic Performance of Reinforced Concrete Buildings on a Pile Foundation in Liquefiable Deposits. *Structures* **2026**, *87*, 111557. [[CrossRef](#)]

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.