Research Review on the Influence of Hammering Pile Vibration on the Surrounding Environment

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Abstract. To enhance the understanding of the influencing factors of hammering pile driving vibration on the surrounding environment, this study aims to investigate the vibration source, propagation laws, and impact range during the construction process of hammering pile driving. The goal is to mitigate the adverse effects of vibration on individuals, nearby structures, and sensitive instruments. This paper provides a systematic review of current engineering practices and research findings. The source and propagation law of construction vibration, as well as the vibration frequency characteristics of hammering pile driving, are analyzed. The field monitoring and numerical simulation research progress on the vibration response of hammering pile driving to surrounding people, buildings, and precision instruments and equipment are discussed. The corresponding vibration reduction and isolation measures are summarized from three aspects: vibration source control, propagation process control, and vibration object control. The main conclusions of the paper are as follows: 1) The vibration generated during the construction process of hammering pile sinking is mainly instantaneous, affecting the surrounding environment in the form of elastic wave. 2) With the increase of distance and depth, the vibration rate decays slowly, and the soil properties are the main factors affecting the vibration propagation and attenuation. 3) The main frequency of the vibration is close to the natural frequency of the building. Operating in close proximity can affect the surrounding environment. However, the superposition effect of ground vibration is not significant, and the affected area remains constant regardless of the amplitude or frequency of the pile-sinking force. 4) The most economical and effective measure to reduce the vibration hazard of hammering pile sinking construction is to set up a vibration isolation trench near the protected object. At present, based on existing research, the design of vibration damping measures for this type of construction primarily relies on vibration isolation along the propagation path vibration isolation, the method is relatively straightforward, but there are shortcomings in the research concerning the impact on and protection of precision instruments and equipment during operation. It is necessary to study the applicability of vibration

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isolation measures along the propagation path for protecting precision instruments and equipment in the near field. This will help advance research on safeguarding precision instruments and equipment.

Keywords: penetration of pile with hammer blow, construction vibration, vibration effect, vibration propagation, adjacent building, precision instrument and equipment, vibration control

1 Introduction

With the rapid development of China's economy and the acceleration of urbanization, mega-cities continue to emerge. As cities expand, the demand for construction land also increases. According to the Statistical Bulletin on National Economic and Social Development of the People's Republic of China in 2022 issued by the National Bureau of Statistics in February 2023, the total supply of state-owned construction land for the entire year was 766,000 hectares, marking a 10.9 percent increase over the previous year. Of this total, industrial and mining storage land covered 198,000 hectares, an increase of 13.2%; real estate land (commercial service land and residential land) accounted for 110,000 hectares, a decrease of 19.4%; and infrastructure land spanned 458,000 hectares, marking a 20.7% increase [1]. The expansion of construction land, the large-scale construction of urban rail transit, and the expansion of renovation and expansion projects lead to many problems, such as a narrow construction site, close proximity to adjacent buildings, and significant construction vibrations. The aforementioned issues can easily have a negative impact on neighboring buildings or the precision instruments and equipment.

Vibration is often considered a negative factor in engineering. Many engineering examples demonstrate that when hammering or vibration methods are used for pile driving construction, dynamic compaction, blasting, and other engineering activities, elastic waves are generated in the soil, disturbing the surrounding soil. Destroying the stress state and structure of the soil may cause uneven settlement, leading to cracks in surrounding buildings, road pavements, underground pipelines, and even ancient cultural relics buildings. Affecting the normal service life, destroying the cultural heritage, and even posing a security threat [2]. For example, during the construction of the Xi'an subway, 16 subway tunnels passed under the Ming city wall in Xi'an, causing the foundation of the city wall to sink and the cracks in the wall to expand [3]. At the same time, the soil vibration caused by elastic waves may affect the resonance or accuracy of nearby equipment in operation, such as electrical equipment or precision instruments, exacerbate the wear of the machine, and reduce its service life [2].

Therefore, it is crucial to assess the vibration impact of pile driving with a hammer to guarantee the stable and safe operation of surrounding buildings and equipment, safeguarding lives and property. It is essential to control the vibrations resulting from pile driving within a safe range. This paper reviews previous engineering practices and existing research achievements from three aspects: the source and propagation law of construction vibration, the influence of hammering pile driving vibration on the surrounding environment, and the vibration control measures for hammering pile sinking. The existing problems and the direction of follow-up research are discussed to provide a useful reference for advancing research on the influence and control of hammer pile construction vibration.

2 Construction Vibration Source and Propagation Law

2.1 Construction Vibration Source

At present, the most common vibrations generated during the construction process include pile driving, dynamic compaction, blasting, and other construction activities. According to the different mechanisms of vibration sources, they can be divided into instantaneous vibration and steady-state vibration [2]. The first type of instantaneous vibration is mainly caused by activities such as hammering pile sinking, dynamic compaction, blasting, and other processes involving sequential or single shocks. The main feature is that the near-source vibration is significant, and the vibration from the previous shock has essentially dissipated before the next shock occurs. The second type of steady-state vibration primarily arises from vibration pile driving, vibration-impact construction, and similar activities, involving continuous harmonics or other periodic waves.

Pile foundations, an ancient form of foundation, were used to support houses with wooden piles at the Hemudu Site 7000 years ago. In recent years, with the acceleration of urbanization and the rapid development of China's economic construction, piles are being increasingly utilized. According to incomplete statistics, tens of millions of piles have been used annually in China over the past 20 years. Pile foundations can be used when there are large vertical or horizontal loads, uneven settlement, a high groundwater level, a weak bearing layer, and other similar conditions. In addition to the above cases, piles are also extensively utilized in foundation pit retention and anchoring structures, as well as anti-slide piles for landslide mitigation [4].

There are various types of piles, which can be categorized into precast piles and cast-in-place piles based on their manufacturing methods. Precast piles are commonly utilized in real-world projects due to their benefits, including assured pile quality, a high level of construction mechanization, and rapid construction speed. The construction methods for precast piles mainly include hammer pile driving, vibration pile driving, static pile driving, water injection pile driving, and others [5].

2.2 Vibration Propagation Law of Hammer-Sinking Pile

Hammering pile driving construction involves the use of machinery such as diesel hammer, hydraulic hammer, and others. The pile hammer falls and impacts the top of the pile, generating a significant force that travels through the pile into the ground. This process results in foundation vibrations. Each impact will produce varying degrees of vibration. The interval of impact time is fixed, with the impact time of a single pile driving being 0.4 ~1s, and its vibration has a certain continuity and regularity.

Hu [6] utilized the TST5926E large-scale structure dynamic characteristic test and analysis system to monitor the vibration during the construction of prestressed pipe piles in the eastern upstream area of a bridge extension project in Guilin. The data show that the peak vertical and horizontal vibration velocities at 3m are 23.18 mm/s and 26.11 mm/s, respectively, and those at 6m are 12.11 mm/s and 15.74 mm/s, respectively. The peak value of the vertical and horizontal vibration velocity power spectrum of the vibration source is close to that of the vibration level. The peak frequency of the vibration in the two directions is similar, and the main vibration frequency is concentrated in the range of 10-25 Hz. The law of vibration propagation states that the closer to the vibration source, the faster the attenuation rate. This effect is particularly noticeable within a range of about 15 meters from the vibration source, where the attenuation occurs rapidly. As the distance increases, the rate of vibration amplitude attenuation slows down gradually.

Zhang [7] used the finite element-infinite element coupling method to develop a three-dimensional finite element model for precast pile hammering pile driving construction. It is also found that the main frequency of vibration caused by hammering during pile driving is low at 3 meters from the pile center, measuring 7.5 Hz. At 20 meters from the center of the pile, the main frequency caused by pile driving with a hammer is approximately 1.5 Hz, which is lower than the frequency observed at 3 meters from the pile center.

Wu [8] compared the response spectrum of earthquakes and pile driving vibrations and found that the ground motion caused by pile driving is similar to that of the earthquake. The dominant frequency of the earthquake is 1 Hz. ~ 3Hz.The frequency of the vibration caused by pile driving is around 10Hz, while the background noise is at 3Hz. The vibration amplitude of pile driving is low. However, because the dominant frequency is close to the natural frequency of typical buildings, the response in terms of acceleration, velocity, and displacement caused by pile driving tends to be amplified. The impact of pile driving on low-rise and multi-story rigid buildings, particularly over a short period, should be treated with caution.

The intensity of pile driving vibration decreases with the increase in soil depth. Richart [9] proposed the curve of horizontal vibration and vertical vibration varying with depth in the case of different Poisson's ratios: as the depth of the soil increases, the attenuation rate from the surface also increases, and the vibration dissipates at a depth of approximately one wavelength.

The primary frequency of pile driving vibration decreases as the pile core distance increases. When the vibration from pile driving construction propagates outward through the soil, the soil acts as a filter. The main frequency of the ground vibration caused by pile driving decreases as the distance from the pile center increases. High-frequency vibrations attenuate rapidly, while low-frequency vibrations attenuate slowly. The vibration gradually becomes dominated by low-frequency vibrations [7], which is similar to the propagation pattern of vibrations caused by underground rail transit and earthquakes [10].

The propagation and attenuation of pile driving vibrations in the soil layer are influenced by soil damping. Kim et al. [11] believe that soil damping can be divided into geometric damping and material damping. Geometric damping is influenced by the type and location of the vibration source, whereas material damping is dictated by soil properties and vibration amplitude.

Soil is the medium through which vibrations propagate, and soil parameters directly influence the propagation of vibrations. Gupta et al. [12] conducted a parametric study on the critical factors influencing induced vibrations in subways. The results indicate that material damping and soil shear modulus play significant roles in vibration propagation. Specifically, the vibration intensity is greater in soft soil. However, the vertical vibration levels in soft and hard soil are similar when the vibration source is distant, and the impact of shear modulus on horizontal vibration is minimal. Athanasopoulos et al. [13] measured Rayleigh wave propagation at several locations in Greece, analyzed the results using the Bornitz attenuation equation, and determined the wave attenuation rate. They also established a relationship between distance and soil modulus that fits well with the measured data. It is considered that the attenuation degree of hard soil material to seismic waves is smaller than that of soft soil.

Zhou et al. [14] conducted a study on the third phase project of Huaneng Shang'an Power Plant, focusing on monitoring ground vibrations during the construction using the precast pipe pile hammering method. They concluded that the vibration impact on the ground originates from the pile tip, and that the peak vibration velocity of the ground increases with the strength and stiffness of the soil layer. At the same time, the attenuation law of ground vibration velocity in the vertical and horizontal directions during pile foundation construction can be well fitted by a negative power function.

3 The Influence of Hammering Pile Vibration on the Surrounding Environment

At present, many countries have identified vibration as one of the seven major environmental public hazards. Japan has conducted a survey on the public complaint rate regarding various environmental vibrations, with construction being the primary cause, accounting for approximately 49.2% of complaints. The survey shows that construction is the main cause of vibration [15], as shown in Figure 1.

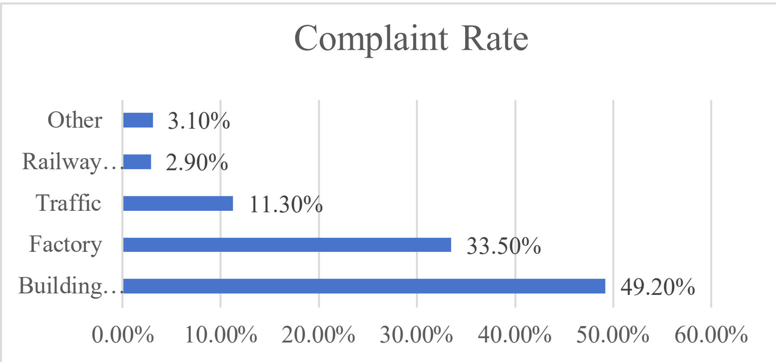

Fig. 1. Public complaints rate of environmental vibration [15]

When evaluating the impact of pile driving vibration on the surrounding environment, it is essential to define the scope of evaluation. Xia et al. [16] suggest that the evaluation scope is influenced by the intensity of the vibration source, construction machinery parameters, geological conditions, and other factors. The measurement of a large number of construction vibration rings shows that the vibration caused by pile driving meets the requirements of environmental vibration standards at approximately 50m during transmission along the surface. When the general environmental vibration measuring instrument is used to monitor a distance of about 100m, it falls below the minimum range of the instrument. Therefore, Xia and others suggest that the evaluation range should be set at 100m.

3.1 The Influence of Hammering Pile Vibration on Buildings

The evaluation methods of the impact of hammering pile driving vibrations on adjacent buildings include the response spectrum method, intensity method, peak velocity method, safety distance method, and others. The peak velocity method and the safe distance method are part of the single-parameter method, which selects either the peak velocity or safe distance as the control parameter to assess the impact of vibration. Although widely used, this method is considered conservative and has poor adaptability. The intensity method follows the concept of seismic intensity, taking into account the frequency spectrum characteristics of vibration waves and the natural frequency of buildings. The law of response spectrum is more accurate. Through the analysis of frequency spectrum and response spectrum of buildings, the dynamic response, stress, and strain of structures are calculated. However, the amount of calculation involved is extensive, making it challenging to obtain the necessary data [17].

In existing research, particle vibration velocity is considered the standard for controlling and characterizing vibration characteristics when analyzing structures. In the relevant national codes, regulations, and a large number of research literature, the peak particle velocity is considered the most suitable parameter for assessing structural damage due to vibration.

Field Monitoring.

As the most widely used prefabricated pile sinking method, many researchers have conducted field detection at construction sites of hammer-driven piles and have drawn various conclusions.

Xu et al. [18] tested the construction vibration of a foundation treatment site for a grain depot under construction and found that the maximum peak speed in a nearby building was 4.92 mm/s. Combined with the existing relevant norms at home and abroad, a safety threshold of 5 mm/s for vibration was established. This determination indicated that the impact of construction vibration from the project was within the safe range.

Yao et al. [19] conducted a study on the cracks in the surrounding civil house walls caused by the construction vibration from precast high-strength concrete (PHC) pipe pile driving in a nearby village. They used a 941B vibration pickup for on-site monitoring and concluded that the duration of ground vibration caused by pile driving ranged from 0.6 to 0.9 seconds. They also found that the vibration energy is partially amplified due to the higher hammering frequency, softer foundation, and shorter hammering interval compared to the vibration attenuation time. Among them, the superposition of vibration energy on the second floor of the building is significant. During the construction phase, two pile drivers are operated simultaneously, resulting in continuous vibrations in the building at specific intervals. This leads to fatigue damage, resulting in numerous cracks in village houses. The vibration damage on the second floor is more severe than that on the first floor.

Hu [6] uses a 941B ultra-low frequency vibrometer to monitor the vibration of the main structure of the target house. Under the most unfavorable working conditions, the maximum amplitude peaks of vertical, horizontal, and radial velocity are 10.55 mm/s, 8.82 mm/s, and 8.66 mm/s, respectively. The vertical velocity-time history curve of the house is shown in Figure 2. The peak interval is 1.5 seconds, and the peak frequency is 10 Hz, which is similar to the 10-25 Hz range of the main frequency of pile driving vibration. It may cause structural resonance, but the pile driving vibration source belongs to instantaneous impact vibration. The duration of impact vibration is 0.4-0.5 seconds, with an interval of about 1.2 seconds. This will not lead to continuous forced resonance of the structure.

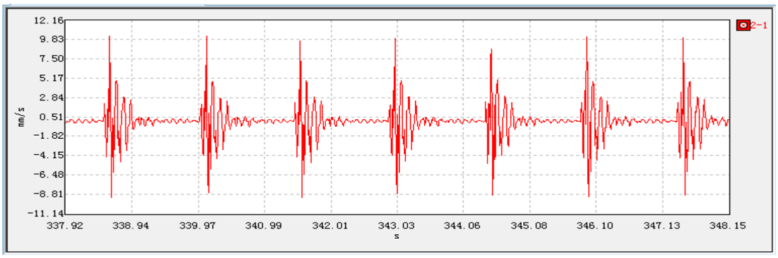

Fig. 2. Vertical velocity time-history curve of the building (15m away from the soft ground vibration source, 4m depth of the vibration source)[6]

Lu et al. [20] conducted vibration monitoring during the expansion project of a power plant to assess the impact of dynamic pile driving vibration from precast high-strength concrete (PHC) pipe piles on the existing factory area. They utilized an 891-II sensor and amplifier for this purpose. The maximum vertical vibration velocity occurs 10 meters away from the pile test point, measuring 1.454 cm/s, which exceeds the 0.3 cm/s limit. The vibration isolation trench, 2 meters wide and 8 meters deep, is being excavated simultaneously. After passing through the vibration isolation trench during the monitoring process, the vibration speed is significantly reduced by 15% to 47%, resulting in a noticeable impact.

Numerical Simulation.

With the development and improvement of finite element software, simulation analysis can reduce the cost and time consumption of on-site monitoring. It can also better model the more complex pile-soil interaction and vibration attenuation during the pile driving process, making a significant contribution to actual engineering projects.

The soil itself is a semi-infinite space. During the finite element simulation, the fixed boundary may cause reflection of the outwardly propagating wave, leading to distortion in the results. At present, the common solution is to use a large interval to absorb most of the energy reflected back through material damping. However, this approach requires a large calculation amount. Artificial boundaries are also utilized, such as viscous boundaries, truncated boundaries, viscoelastic boundaries, and infinite element boundaries [21]. At present, in the simulation of hammer pile sinking, the infinite element boundary is used to simulate the soil in the semi-infinite domain. This approach can accurately reflect the actual boundary conditions and reduce calculation time.

Zhang et al. [22] established a fundamental two-dimensional finite element model to simulate pile driving using PLAXIS 2D. They studied the effects of soil damping ratio, soil Young's modulus, and the number of loading pulses during pile driving on ground vibration. It is concluded that a higher damping ratio and a higher Young's modulus can reduce the intensity of ground vibration. Additionally, the superposition effect of multiple loading pulses on ground vibration is not significant when the time interval between two continuous loading pulses is 0.99 seconds.

Ekanayake [23] established the ABAQUS/Explicit finite element model using the Arbitrary Lagrangian Euler (ALE) method. The study focused on investigating the impact of hammering pile driving, vibration pile driving, soil stiffness, soil material damping, as well as the amplitude and frequency of pile driving force on the vibration attenuation law. The model was verified using field data from pile driving engineering and was evaluated in conjunction with national vibration safety standards to determine the impact range of vibration from pile driving. The results show that the influence area of pile driving does not change with the amplitude or frequency of the pile driving force.

Zhang et al. [7] established a three-dimensional finite element and infinite element coupling model in ABAQUS to conduct a comparative analysis of the hammer method and vibration method for pile driving. They verified the model with measured data. The results indicate that vibration safety control standards can help reduce vibrations. A threshold of 5 mm/s is recommended for hammer driving piles. The vibration influence range of a pile driven by the hammer method is extensive, reaching up to 10~15 meters.

Lin et al. [24] utilized ABAQUS in conjunction with infinite element theory to simulate the three-dimensional finite element pile driving process. Compared with the dynamic data collected at the construction site of a real estate development project, the law of vibration attenuation is summarized, and the range of influence is determined. The results indicate that when using the hammering method, the velocity of the soil body demonstrates a trend of attenuation. The peak velocity of oscillation occurs at a frequency of 0.5Hz, with the main frequency concentrated between 3.8 and 6 Hz. These frequencies fall within the low-frequency oscillation range and are influenced by damping effects, resulting in a gradual attenuation. Under the construction condition of single pile hammering method, the influence ranges of industrial, civil, and sensitive buildings are 12.5 m, 14 m, and 22 m respectively.

Xu [25] established a model to calculate the vibration impact of pile driving at a test site in Zhongshan City. The model utilized the Mohr-Coulomb model within the FLAC3D nonlinear dynamic analysis framework and was compared with the actual field monitoring data. The results show that the peak vibration velocity of each particle decreases exponentially with the increase in the distance from the hammer point, and the attenuation velocity is the fastest at shorter distances. The three-way vibration velocity of the same particle is Z > X > Y. Therefore, it is reasonable to select Z vibration velocity as the peak value of vibration velocity in the safety evaluation of buildings. After comparing the calculated results with the field monitoring data, the Z-velocity and the closing velocity show good agreement.

3.2 The Influence of Vibration on Ancient Buildings and Precision Instruments

The Influence of Vibration on Ancient Buildings.

At present, in the relevant research on the influence of vibration on ancient buildings, the predominant source of vibration is traffic-induced vibrations. Most of the ancient buildings in China are brick and wood structures. Compared with the ancient buildings with masonry structures in Europe, Chinese ancient buildings are more fragile. Vibrations can cause significant damage to these ancient buildings, which have stood for nearly a thousand years, leading to issues like cracks, settlement, and so on. Once these damages occur, they are difficult to repair. Once ancient buildings are destroyed, they become non-renewable, resulting in a significant loss of historical and cultural heritage. For example, Meng [26] conducted numerical simulations and evaluated the traffic vibration response to the influence of subway vibrations on the Xi'an Bell Tower. The results show that the horizontal vibration velocity of the wooden structure of the Xi'an Bell Tower, caused by the combination of existing ground traffic and subway operation, has exceeded the allowable value specified in the technical code for preventing industrial vibrations in ancient buildings (GBT50452-2008) [27]. The recorded velocity is 3.33 times higher than the allowable limit. Corresponding shock reduction and isolation measures must be taken to protect the safety of the Xi'an Bell Tower.

The Influence of Vibration on Precision Instruments.

With the development of high-precision technology and fine instruments and equipment, the research on micro-vibration and vibration isolation measures is increasing to ensure the smooth operation of precision instruments. Precision manufacturing, nano-materials, microelectronics, optical instruments, and many other precision instruments have sensitive elements. Prolonged vibration of these sensitive elements can lead to their failure or a decrease in accuracy. Currently, research on the influence of needles on traffic vibrations on precision instruments and equipment is more comprehensive. The environmental vibration caused by traffic is shown in Figure 3.

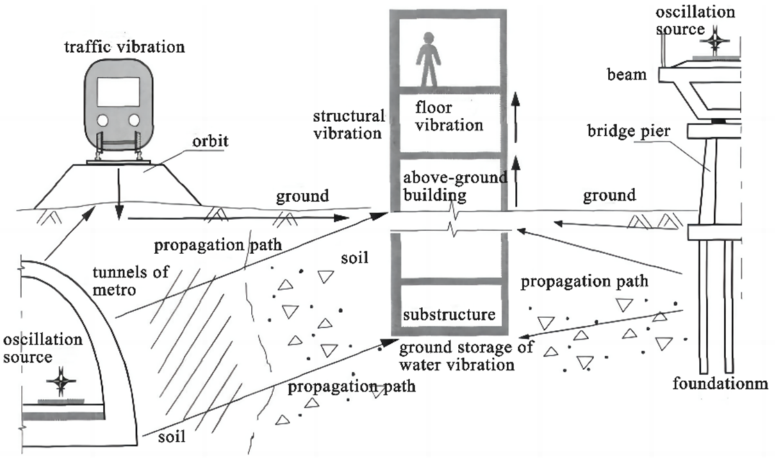

Fig. 3. Environment vibration induce by mass traffic system[29]

Beijing has gathered a large number of scientific research institutions. A notable example is the impact of vibrations caused by Beijing Metro Line 4 on the precision instruments and equipment in laboratories. Liu [28] conducted outdoor and indoor tests in the physics laboratory at Peking University. During the test of the working environment of the Tecnai30 electron microscope in the Beijing University Laboratory, the primary source of vibration was found to be road traffic, ranging from 8 to 20Hz. At present, environmental vibrations have little influence on the precision instruments in the laboratory. However, the movement of staff in the laboratory can affect the use of the Tecnai30 electron microscope. It shows that the precision instrument is very sensitive to vibration frequency. Sun [29] studied the impact of subway train vibrations on precision instruments and equipment at Peking University Science Test Base, with Beijing Metro Line 4 as the backdrop. The study focused on the surface vibration response patterns and the damping performance of steel spring floating slab tracks. It is considered that the primary frequency of subway train surface response is 30 ~80Hz and that of road traffic flow is 10 ~ 30Hz. Both of them cause the surface vibration response to have a superposition effect at the same frequency. The installation of a steel spring floating plate track can accelerate the attenuation gradient of surface vibrations and meet the operational requirements of precision instruments and equipment in the building.

Aiming to investigate the impact of construction-related vibrations on precision instruments, Cheng et al. [30] conducted a study using the close proximity of a road construction site in Wuxi near the Nikon Optical Instrument Factory as the research setting. The study measured the environmental vibration velocity caused by vibratory rollers near the location of precision instruments. Combined with the VC standard (Vibration Criteria) [31], it shows that the ground vibration velocity and vertical Z vibration level caused by road rollers gradually decrease with the increase of the vibration center distance. It is predicted that the vertical Z vibration level at the location of the precision instrument is nearing the limit of the VC-A curve, which largely complies with the control standard set by the company. However, it also shows that the vibration from nearby construction activities will affect the normal operation of the precision instrument.

Zhang [32] relied on the construction project for the precision gravity measurement reconstruction and expansion of a cave laboratory on a university campus. There are a large number of high-precision measuring instruments and buildings around the new cave laboratory that are very sensitive to the disturbance caused by construction. Through the comparison between the predicted and calculated values, it was observed that when the blasting face reaches the precision laboratory and the old cave tunnel, the predicted values of the vibration velocity calculated using the Sadaovsky formula exceed the allowable limit of the project's vibration velocity. This discrepancy fails to meet the safety requirements for construction. After optimizing the blasting parameters, the deformation values in all directions are significantly lower than the deformation control standard, indicating that the optimization design is both reasonable and effective.

According to the above research, current studies on the influence of vibrations on ancient buildings and precision instruments primarily concentrate on traffic vibrations. However, there is limited research on construction vibrations, and few studies have explored the effects of pile driving vibrations on precision instruments and equipment. Traffic vibration is a kind of long-term and continuous vibration, whereas the vibration resulting from the impact load of pile driving belongs to instantaneous vibration. In the case of the same center distance of vibration, the influence of single vibration on precision instruments and equipment is greater than that of traffic vibration. At the same time, the precision instruments involved in the research are mainly related to the electronic industry-related instruments and equipment, and do not include vibration-sensitive or vulnerable equipment such as substation electrical equipment in operation. Subsequent research should pay active attention to these two aspects.

4 Hammer Pile Vibration Control Measures

Considering the influence of hammering pile driving vibrations on nearby individuals, structures, and delicate instruments, it is essential to take vibration control measures to reduce the adverse effects of construction vibrations and prevent irreversible damage. Combined with the vibration source and propagation laws in the construction process of hammering pile driving, vibration isolation measures can be divided into three types: vibration source control, propagation process control, and vibration object control [33].

4.1 Vibration Source Control

In pile construction, it is recommended to replace the diesel hammer with a hydraulic hammer to reduce noise and pollution. Alternatively, static pressing piles can be used when there is no medium-dense sand interlayer soil thicker than 2m, provided that the geological conditions of the soil layer meet the requirements. If the construction method with less vibration cannot be adopted, more attention should be paid to vibration control during the propagation process and the protection of the vibrated object.

For traffic vibration and other construction-related vibrations, control measures can be implemented, such as using steel spring floating slab tracks [29] or optimizing construction parameters [32].

4.2 Propagation Path Control

The impact of hammering pile driving vibration on the environment mainly depends on the generation of elastic waves that disturb the surrounding soil, leading to the disruption of the stress state and structure of the soil. Effectively blocking the propagation path of elastic waves can help control the vibrations caused by pile driving with a hammer. At present, the most commonly used method for controlling the propagation process is to establish a vibration isolation trench, which can be either an empty trench or a filled trench. The main reason for the formation of filling ditch is that the construction of empty ditch needs support and maintenance is difficult.

The research on the application of vibration isolation trenches began in the last century. Woods et al. [34] first conducted experimental research on the performance of vibration isolation trenches to reduce ground vibration. The results show that using open trenches as vibration isolation barriers, the depth of open trenches that constitute effective vibration isolation should be 0.33 ~ 1.3 times the Rayleigh wavelength. A vibration isolation trench requires a minimum depth of 0.6 times the Rayleigh wavelength to reduce the ground amplitude by 75%.

Taking the third phase project of Huaneng Shang'an Power Plant as the background, Zhou et al. [14] measured and studied the ground vibration characteristics during the construction of prefabricated piles, and analyzed the vibration reduction effect of the vibration reduction ditch. After setting the damping ditch, the average value of the vertical velocity is 0.58 ~ 0.63 before the damping, and the average value of the horizontal radial component of the velocity is 0.53 ~ 0.85 before the damping. The measured data show that the vibration velocity of the particle is obviously reduced. For the vibration with deep vibration source, it is an effective vibration reduction method to excavate the damping ditch near the protection object.

Chen et al. [35] conducted a numerical simulation using a coupled system calculation program that integrated axisymmetric elastic finite element analysis and artificial boundary conditions. They compared the results under similar engineering conditions. They believed that using a vibration isolation ditch is an effective method to reduce the vibrations caused by pile driving. It has little effect on the vibration isolation of the soil on the same side of the pile; the larger the difference between the elastic modulus of the filling material and the soil in the ditch, the more pronounced the vibration isolation effect becomes. Under the condition of ensuring the stability of the ditch slope, the unfilled ditch provides the best vibration isolation effect. The vibration isolation effect increases with the depth of the ditch, generally at 0.6 times the wavelength, which is independent of the width of the ditch. Under certain conditions, the closer the protected object is to the ditch position, the better the vibration isolation effect will be.

Li [36] established the vibration source-soil layer-vibration isolation ditch model. He analyzed the vibration isolation effect of materials such as bentonite, rubber, and polystyrene foam. Additionally, he examined the acceleration, velocity, and displacement response of the soil behind the ditch. The study concluded that polystyrene is the most effective material for vibration isolation. But the vibration isolation effect of an empty ditch is better, with the vibration isolation effectiveness ranking as follows: V-shaped ditch > trapezoidal ditch > rectangular ditch > step ditch.

4.3 Vibrating Object Control

The protection of vibrating objects primarily targets buildings and precision instruments and equipment. Similar to structures and equipment impacted by earthquakes, the utilization of energy dissipation products like dampers or isolation bearings can significantly enhance the anti-vibration capabilities of buildings and equipment. At present, the common energy dissipation products used in building structures include viscous damper, viscoelastic damper, metal damper, friction damper, composite damper, buckling restrained braces, etc. Beijing New Airport adopts a vibration control form combining shock absorption and isolation, and more than 100 sets of new viscous dampers are arranged in the isolation layer, as shown in Figure 4 [37]. For ancient cultural relics, regular repair, reinforcement, or real-time monitoring of vibrations during construction is a good means of protection [33]. For precision instruments and equipment, specific vibration isolation technology or more advanced active vibration isolation technology can be used.

Fig. 4. Installation of viscous damper in isolation layer [37]

In 2013, a magnitude 7 earthquake struck Lushan County, Sichuan Province. Following the powerful earthquake, the outpatient comprehensive building of Lushan County

People's Hospital, which utilized isolation layer, lead-core rubber isolation bearing, and ordinary rubber isolation bearing isolation technology, did not have any damage to the window glass. There were no cracks in the internal beams, columns, and wall components of the building, and the isolation effect was remarkable [37].

Aiming to explore seismic isolation technology for precision instruments, this paper uses precision electrical equipment as a case study. At present, research on shock absorption technology for electrical equipment is still relatively scattered, and there is no unified theoretical system. It primarily leverages the shock absorption technology used in buildings and then enhances and adapts it based on the specific model characteristics of various electrical equipment. For equipment with a high shape, large weight, and a low center of gravity in the power system, such as transformers and reactors, damping measures are implemented by setting isolation devices between the foundation and the equipment body. For example, Feng et al. [38] developed two isolation systems: a sliding bearing and rubber bearing combination system, and a segmented high damping rubber bearing combination system. Liu [39] introduced lead rubber bearings and lead shock absorbers into disconnectors and arresters. Ma et al. [40] combined laminated rubber bearings and sliding bearings to create a composite isolation bearing system, which is arranged as shown in Figure 5.

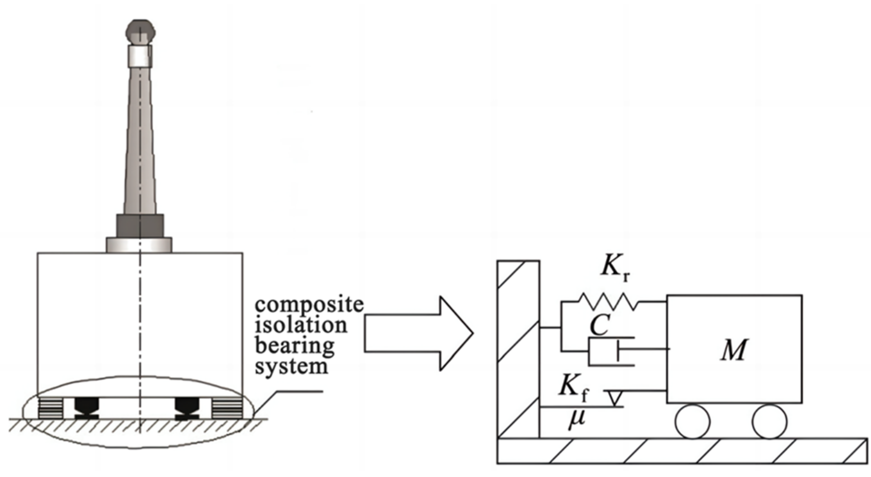

Fig. 5. Schematic diagram of a base-isolated transformer[40]

For special electrical equipment with a high body shape, high center of gravity, and heavy weight in the power system, such as arresters, transformers, disconnectors, and other equipment, damping measures like setting dampers and increasing stiffness are primarily employed [41]. Kong et al. [42], and Puff et al. [43] established an isolation system composed of steel wire ropes and viscous dampers. Xie et al. [44] [45] proposed a composite damping bearing consisting of steel wire rope and a hydraulic damper for UHV T-type bypass switch with strict displacement limitations, as shown in the Figure 6. China Electric Power Research Institute proposed a lead damper for pillar electrical equipment and has conducted extensive research on lead dampers.

You et al. [46] designed a lead damper suitable for circuit breakers based on the structural characteristics of circuit breakers. Zhang et al. [47] [48] applied lead dampers to UHV porcelain arresters.

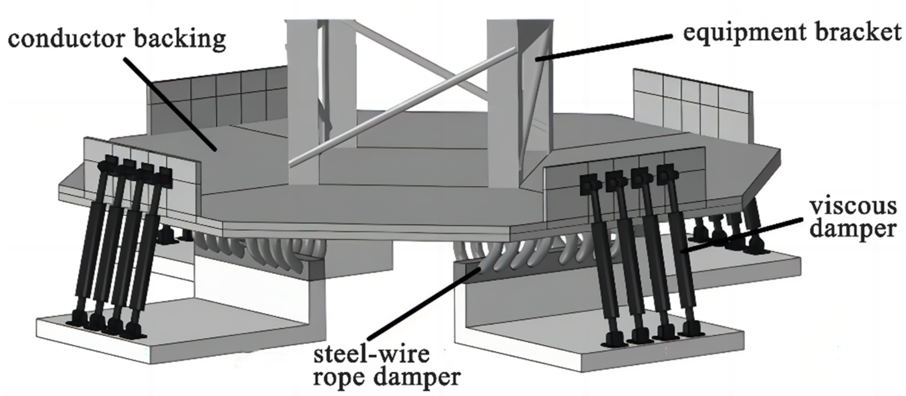

Fig. 6. Diagrammatic sketch of the base isolation[45]

5 Conclusion

In recent years, with the process of urbanization, the expansion of construction land has led to many problems: the narrow construction site and the close distance from adjacent buildings. Due to the wide application of pile foundations, hammer pile driving is commonly used in construction sites due to its cost-effectiveness. The vibration caused by hammering during pile driving will inevitably impact the surrounding environment.

This paper systematically reviews the influence of construction vibration on the surrounding environment during the process of pile driving with a hammer. It summarizes and analyzes the sources and propagation laws of vibration, the impact of pile driving vibration on the surrounding environment, and the vibration control measures for pile driving with a hammer. The main conclusions are as follows:

1) The vibration generated during the process of hammering piles for sinking construction is primarily instantaneous. The interval fixation of impact time has a certain continuity and regularity, which affects the surrounding environment in the form of elastic waves.

2) With the increase in distance and depth, the vibration rate decreases slowly and is gradually dominated by low-frequency vibrations. The main factors affecting the propagation and attenuation of vibrations during pile sinking are the soil properties. The hard soil exhibits a high peak value of vibration velocity and slow vibration attenuation.

3) According to field monitoring and numerical simulations, the primary frequency of the vibrations caused by pile driving is near the natural frequency of the building. The vibrations from nearby construction activities can disrupt the normal functioning

of the building and precision instruments. However, the superposition effect of ground vibration is not apparent, and the affected area does not change with the amplitude or frequency of the pile-sinking force.

4) Many researchers have studied the impact of vibrations generated by pile-driving construction on neighboring people, buildings, precision instruments, and equipment. At present, the most economical and effective measure to reduce the vibration hazard of hammering pile sinking construction is propagation path control, which involves setting up a vibration isolation trench near the protected object.

As a widely used method of pile sinking, many researchers have studied the influence of its vibration. The main research object is the building, and the research methods include field monitoring and numerical simulation. The research on the influence of precision instruments and equipment mostly focuses on traffic vibration. However, there are few studies on the impact of hammering pile vibration on precision instruments and equipment. At the same time, the design of construction vibration reduction measures mainly depends on isolating vibrations along the propagation path. The method is relatively simple, but there are also deficiencies in the research on the impact and protection of precision instruments and equipment during operation. The next research recommendations are as follows:

1) Conduct research on the impact of vibrations generated by pile driving construction on precision instruments and equipment, particularly electrical equipment in substations, with insufficient consideration and increased susceptibility. Consider the natural frequency of precision instruments and equipment to explore the influence of hammering pile driving frequency and other factors on them. Avoid forced resonance to prevent damage.

2) Conduct research on the effectiveness of propagation path vibration isolation measures for safeguarding in-service precision instruments and equipment in the near field. Additionally, advance research on the influence and protection of construction activities in close proximity to in-service precision instruments and equipment.

3) The numerical analysis of the coupling between soil, precision instrument equipment, and building due to vibration from pile hammering during construction is conducted, taking into account their dynamic interaction.

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References

1. National Bureau of Statistics. (2022) Statistical Bulletin on National Economic and Social Development of the People's Republic of China in 2022. https://www.gov.cn/xinwen/2023-02/28/content_5743623.htm.
2. Jia M C et al. (2004) Review on Vibration during Foundation Treatment and Its Influence on the surrounding Environment. UNDERGROUND SPACE, 04: 500-505+565.

3. Lai J X, Zhou H, Wang K, et al. (2020) Shield-driven induced ground surface and ming dynasty city wall settlement of Xi′an metro. Tunnelling and Underground Space Technology, 97: 103220.
4. Zhou J X, Li G X, et al. (2015) Foundation Engineering. TSINGHUA UNIVERSITY PRESS, Beijing.
5. Guo Z X. (2020) Civil Engineering Construction. Southeast University Press, Nanking.
6. Hu Q X. (2017) Vibration monitoring and extremum analysis of prestressed pipe pile construction. Guilin university of technology.
7. Zhang Z M, Huang H T and Zhang J H. (2017) An Investigation of Surrounding Impacts Caused by Hammering and Vibration Pile-driving. Chinese Journal of Underground Space and Engineering, 13(04): 1129-1136.
8. Wu X B. (2017) Comparative Analysis on the Response Spectra of Blasting Piling and Seismic Oscillation. Fujian Construction Science & Technology, 02: 30-32.
9. Richart F E, et al. (1970) Vibration of soil and Foundation. Prentice-Hall Inc, New Jersey: Englewood Cliffs.
10. Xu G X, Yao L K, Li Z H and Gao Z N. (2008) Dynamic response of slopes under earthquakes and influence of ground motion parameters. Chinese Journal of Geotechnical Engineering, 30(6): 918.
11. Kim D S, Lee J S. (2000) Propagation and attenuation characteristics of various ground vibrations. Soil Dynamics and Earthquake Engineering, 19(2): 115.
12. Gupta S, Stanus Y, Lombaert G, et al. (2009) Influence of tunnel and soil parameters on vibrations from underground railways. Journal of Sound and Vibration, 1/2, 327: 70.
13. Athanasopoulos G A, Pelekis P C and Anagnostopoulos G A. (2020) Effect of soil stiffness in the attenuation of Rayleigh-wave motions from field measurements. Soil Dynamics and Earthquake Engineering, 19: 277.
14. Zhou Q C, Li H B, Li X B, Liu B and Li J R. (2006) Analysis of vibration caused by prefabricated pile’s dynamic driving. Rock and Soil Mechanics, 05: 754-758.
15. Japanese Institute of Noise Control (2001) Regional Vibration of Environments. Jibaotang Press, Tokyo.
16. Xia C Y, Yao Y P and Luo T. (2003) Environmental Impact Assessment of Vibration Induced by Pile Sinking. Journal of Beijing University of Aeronautics and Astronautics, 06: 539-543.
17. Zhang Z, Yuan Y B. (2012) Simulation and evaluation of construction vibration impact based on ABAQUS. Journal of Liaoning Technical University (Natural Science), 31(01) :65-68.
18. Xu X C, Xu H B, Chen S X. (2003) Research on influence of vibration caused by pile construction on environment and countermeasures. Rock and Soil Mechanics, 06: 957-960.
19. Yao D P, Zhang Y F, Xie Z C, Zhuo Q and Zhang Y G. (2008) Discussion on evaluation methods of piling vibration impacting on buildings. WORLD EARTHQUAKE ENGINEERING, 24(04): 142-147.
20. Lu W, Zhao D C and Wang Z R. (2017) Pile Driving Vibration Monitoring and Analysis of a Power Plant Expansion Project. Site Investigation Science and Technology, S1: 221-224.
21. Huang S. (2010) RESEARCH ON FAILURE MECHANISM ANDASEISMIC MEASURES FOR UNDERGROUNDENGINEERING UNDER HIGH INTENSITYEARTHQUAKE. Graduate School of Chinese Academy of Sciences (Institute of Rock and Soil Mechanics).
22. Zhang M and Tao M. (2011) A parametric study on factors affecting ground vibrations during pile driving through finite element simulations // Geo-Risk: Geotechnical Risk Assessment and Management. ASCE: 931-938.

23. Ekanayake S D, Liyanapathirana D S and Leo C J. (2013) Influence zone around a closed －ended pile during vibratory driving． Soil Dynamics and Earthquake Engineering, 28(53): 26-36.
24. Lin Y Q, Wang Q, Chen S H, Zhu S F and Xia Z H. (2019) FEM analysis of hammering pile-driving effect on the surrounding buildings. Journal of Fujian University of Technology, 17(04): 331-336.
25. Xu T. (2021) Three-dimensional Numerical Analysis of Vibration Effect of Piling Construction on Surrounding Buildings. GUANGDONG ARCHITECTURE CIVIL ENGINEERING, 28(12): 51-54+99.
26. Meng Z B. (2009) Analysis and Assessment of the Vibration Responds Traffic-Induced of Xi'an Bell Tower. Xi'an University of Architecture &Technology.
27. Ministry of Housing and Urban-Rural Development of the People’s Republic of China, General Administration of Quality Supervision, Inspection and Quarantine of the People’s Republic of China. (2008) Technical specifications for protection of historic buildings against man-made vibration: GB/T50452-2008. China Architecture & Building Press, Beijing.
28. Liu W F. (2009) Study on Numerical Prediction Model of Metro Train Induced Vibrations in Tunnels and Free Field. Beijing Jiaotong University.
29. Sun X J. (2008) Prediction of Environment Vibrations Induced by Metro Trains and Mitigation Measures Analysis. Beijing Jiaotong University.
30. Cheng L, Wang C B, Xu B and Xu D. (2017) Study on the Influence of Roller Induced Vibration on Sensitive Instrument. Science Technology and Engineering, 17(07): 143-147.
31. IEST-RP-CC012.2, IEST-RP-CC012.2. Considerations in Cleanroom Design, (2007).
32. Zhang C C. (2021) Research on the Influence Control of Tunnel Construction on the Adjacent Sensitive Laboratory and Its Surrounding Buildings. Beijing Jiaotong University.
33. Xu R Q, Guo Z, Ding P, Chen W X, Li J H, Zhu H D, and Zhang B L. (2021) Overview on Influence of Vibration Induced by Shield Construction on Adjacent Buildings and Its Control Measures. Tunnel Construction, 41(S2): 14-21.
34. Woods R D. (1968) Screening of surface waves in soils. Journal of the Soil Mechanics and Foundations Division, ASCE, 94(4): 951.
35. Chen Y M, Ling D S and Zhou C T. (2020) Numerical Analysis and Test of Pile Driving Vibration. Journal of Vibration Engineering, 02: 58-64.
36. Li Q. (2020) Research on the Vibration Isolation Performance of a New Type of Trench. East China Jiaotong University.
37. Zhou Y, Shang C H and Zhang C. (2019) Progress in research and application of energy-dissipated technology. Building Structure, 49(19): 33-48.
38. Feng M Q, Liu G Y and Murota N. (2006) Experimental and Analytical Studies of Base Isolation Systems for Seismic Protection of Power Transformers.
39. Liu Y. (2015) The Analysis of Seismic Shock Protection Performance and Seismic Isolation on the Basis of Electrical Equipment on Substations. Shijiazhuang Tiedao University.
40. Ma G L, Zhu R Y, Xie Q, He C and Xin Z H. (2017) Shake Table Testing of a Base-isolated Transformer Bushing System. High Voltage Engineering, 43(04): 1317-1325.
41. Qiu N, Cheng Y f, Zhong M, Lu Z c, Zhu Z B and Lu X L. (2015) Progress and Prospect in Seismic Research of 1000 kV UHV AC Electrical Equipment. High Voltage Engineering, 041(005): 1732-1739.
42. Kong D and Reinhorn A M. (2009) Seismic Evaluation and Protection of High Voltage Disconnect Switches: Technical Council on Lifeline Earthquake Engineering Conference.

43. Puff M, Kopanoudis A, Seck A V, et al. (2015) Introduction of An Innovative Base Isolation System for Seismic Protection of HV Components Based on A Combination of Wire Ropes and Viscous Dampers. Microelectronics Reliability, 35(3): 377-402.
44. Xie Q, Yang Z, He C, et al. (2019) Seismic performance improvement of a slender composite ultra-high voltage bypass switch using assembled base isolation. Engineering Structures, 194: 320-333.
45. Xie Q, Yang Z Y and He C. (2019) Seismic responses analysis and experimental study of T-shape switch equipment with base isolation. EARTHQUAKE ENGINEERING AND ENGINEERING DYNAMICS, 39(01): 54-61.
46. You H B, Zhao F X. (2011) Effect of Loading Frequency on Dynamic Properties of Lead Alloy Absorber. Technology for Earthquake Disaster Prevention, 06(004): 384-395.
47. Zhang X S, Dai Z B, Cao M G and Lu Z C. (2013) Dynamic behavior of 500 kV metal oxide arresters with a new type of lead dampers. Journal of Chongqing University, 36(07): 66-73.
48. Zhang X S, Ai X Q and Dai Z B. (2014) Seismic Safety Performance Evaluation of 1100 kV Porcelain Arresters with Damper. High Voltage Apparatus, 50(06): 1-6.