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DYNAMIC MONITORING AND VIBRATION MITIGATION OF 15TH-CENTURY STATUES IN A HISTORIC CHURCH IN NAPLES

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Abstract

This paper presents a dynamic monitoring study of a collection of terracotta statues, crafted in 1492, housed within a historic church in Naples. The statues are subjected to a range of ambient vibrations stemming from vehicular and subway traffic, visitors walking, social events within the church, and ground motions due to the ongoing bradyseism activities in the region. The primary objective of the study is to evaluate the vibration levels acting on the statues and to analyse their dynamic response characteristics, particularly their frequency contents under various vibrations.
A Dynamic Monitoring system was deployed to continuously record vibrational data from multiple sources over an extended period. The monitoring data revealed that the artworks exhibit low levels of vibration and maintain a very good safety margin under typical ambient conditions while standing in the podium. However, the vibration levels significantly increase during transport operations for temporary exhibitions in other locations. This elevated dynamic response poses a potential risk to the structural integrity of the statues. To address this concern, the study explores mitigation strategies aimed at minimizing transport-induced vibrations. Recommendations include the use of specialized isolation systems to control vibration response during transit and possible strong ground motions. The proposed solutions are expected to enhance the protection of these culturally significant assets, ensuring their preservation for future generations.

Keywords: Dynamic Monitoring, Human-induced Vibrations, Ambient Vibrations, Cultural Heritage, Frequency Content.

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1 INTRODUCTION

The conservation of cultural heritage is essential for preserving the memory of our past. Ensuring the transmission of artistic and historical objects to future generations requires effective musealization and protection systems. In recent years, significant advancements have been made in safeguarding artistic heritage from harmful environmental factors such as humidity, temperature fluctuations, and chemical interactions. However, scientific literature has primarily focused on mitigating risks associated with seismic events. [1] [2] [3]. However, studies on the vulnerability of cultural heritage to human-induced vibrations, such as those caused by visitors' footsteps, cultural events, nearby construction, and railway or road traffic, remain limited and fragmented. The impact of these vibrations varies depending on the material, shape, size, condition, and mechanical properties of the artwork. Repeated exposure, even to vibrations that are nearly imperceptible, can gradually impose excessive stress on the artwork and its supporting structure, potentially leading to cracking, breakage, displacement of components, and material fatigue over time. [4] [5] [6]. Case studies on museum environments indicate that visitor foot traffic and nearby transportation networks can generate cumulative stress on sculptures and decorative elements, potentially leading to micro-fractures and long-term deterioration. Additionally, shock loads, such as those resulting from dropping or moving an artwork, should also be considered. These high-intensity, short-duration forces can cause immediate and visible damage. A milder form of shock occurs when a transport case comes to a bump stop at the bottom of an unloading ramp or when a transport cart is rolled over a rough surface. [7] [8] [9].

Currently, there are no universally established criteria for assessing the risks that human-induced vibrations pose to artworks. Existing international standards, such as UNI 9916:2014 [10] and DIN 4150 [11], primarily address the effects of vibrations on residential buildings, industrial facilities, and monumental structures. However, these guidelines are not specifically tailored to the unique characteristics of museum artifacts. The need for dedicated standards on allowable human-induced vibrations in cultural heritage extends beyond defining acceptable vibration levels; it also requires a deeper understanding of the relationship between cyclic load magnitude and the number of loading cycles that can lead to damage. Research conducted over the past decade suggests that for traditional paintings in good condition, a vibration limit of 2 mm/s can be considered a safe lower threshold for events lasting up to six months. These events include transport, construction activities, single music concerts, and traffic near museums, with mixed vibration frequencies below 50 Hz. However, for other types of artifacts, such as statues and sculptures, there is significantly less research available. Nonetheless, 2 mm/s also appears to be a reasonable threshold at which the risk of damage remains low. It is important to note that while this limit represents a low-risk threshold, it does not guarantee the complete absence of damage [12]. Continuous monitoring and analysis are essential to ensure these vibrations remain within safe thresholds to prevent potential damage to sculptures and other sensitive artifacts.

This study aims at monitoring the transient and consistent vibrations on a set of historic sculptures inside a church induced by various sources and suggesting isolation devices to mitigate their response.

2 CASE STUDY

In the presbytery of the *Sant'Anna dei Lombardi* church in Naples, founded in 1411 in the city's historic centre as a symbol of the magnificence of King Alfonso II of Aragon's court, stands the sculptural group *Compianto sul Cristo morto* (*Mourning over the Dead Christ*). Created in 1492 by Guido Mazzoni, this terracotta masterpiece is a pinnacle of Renaissance artistry, showcasing the sculptor’s remarkable ability to render the varying textures of fabrics, fur, leather, and embroidery through a single material. The composition depicted in Figure 1 consists of seven life-sized statues arranged in a semicircle around the central figure of Christ, lied on the ground after being deposed from the cross. From left to right, the figures include Joseph of Arimathea, Mary Magdalene, Mary of Salome (Figure 2) supporting the lifeless Virgin Mary, St. John the Evangelist, Mary of Cleophas, and Nicodemus. Notably, some of the Aragonese royals are depicted within the scene, with Alfonso II, son of Ferdinand I, portrayed as Joseph of Arimathea. Each statue is characterized by a striking realism and intense emotional depth. The expressions are deeply evocative, capturing an intimate moment of grief through anguished screams, fainting figures, and furrowed brows struggling to hold back tears.

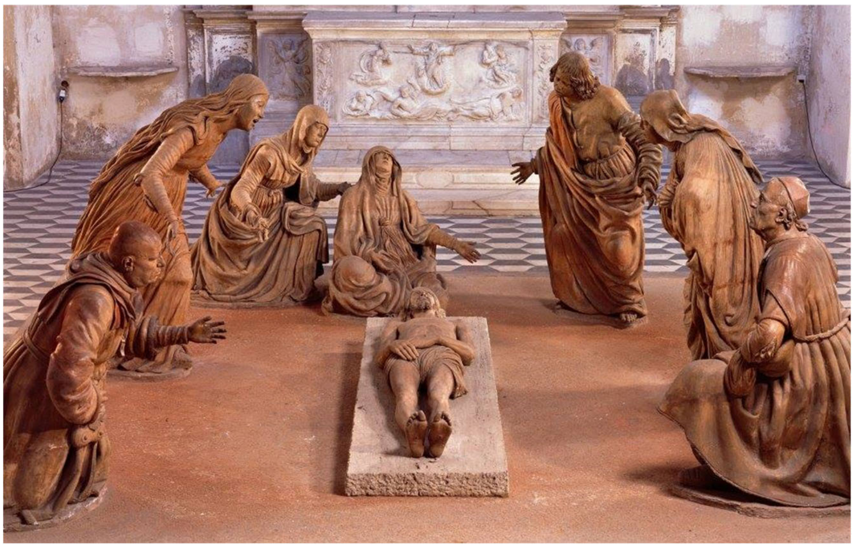

Figure 1: The set of sculptures to be monitored.

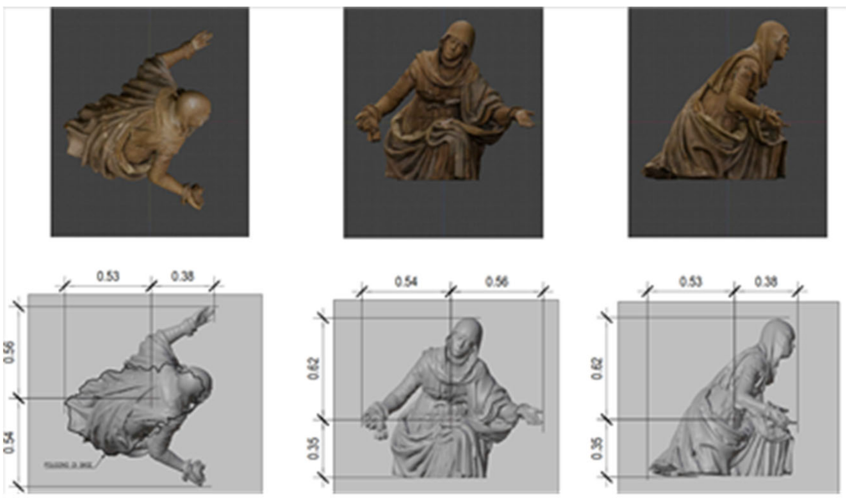

Figure 2: 3D laser scanning of one of the sculptures and its centre of gravity.

3 DYNAMIC MONITORING

A vibration monitoring system was developed to measure vibration levels and automatically communicate this information to the observers. This system, which utilized wireless communication, was deployed in such a way that when predefined vibration velocity thresholds were exceeded, automated alerts were sent via email or SMS to ensure a prompt response. The rationale behind the selected vibration thresholds used in the project is abovementioned value of 2 mm/s to avoid damages on sculptures.

In addition to the quantitative data provided by the monitoring system, daily observations and regular hands-on assessments were conducted to supplement the analysis. While initial testing provided valuable insights, actual construction activities often resulted in unexpected vibration levels, requiring adaptive mitigation strategies. Observations regarding the response of artworks and the building itself to various existing source of vibration, i.e. visitors' footsteps, metro crossing, street traffic, cultural and religious events and possible earthquakes will be presented.

A triaxial velocity transducer was installed on an adjacent wall and on the podium between the sculptures (Figure 3) to measure vibrations from various sources. The measurements were conducted using a SWARM Vibration Monitor, a high-quality velocity transducer that wirelessly transmits data to a web platform for real-time monitoring. If vibration levels exceed the safe thresholds, posing a risk of damage to the objects under study or causing discomfort to residents, instant alerts are sent to users. The SWARM Vibration Monitor utilizes micro-electromechanical systems (MEMS) technology, offering accurate vibration measurements while saving time, cost, and effort. Its compact design (10.9 × 13 × 4.5 cm) and lightweight structure (260 g) allow for quick and easy installation. The measuring frequency range is between 0.5-250 Hz able to measure velocities (in three perpendicular directions, X-Y-Z) in the range ±300.0 mm/s and accelerations in the range ±40 g, with a resolution of 0.5 μm/s, in the and sampling rate of 1 kHz. The users can configure the device remotely and access data anytime via the web platform.

Traditionally, vibration monitoring in the construction sector relied on geophone technology. However, the introduction of MEMS-based sensors has revolutionized the industry, leading to a gradual shift toward these compact and user-friendly devices. MEMS sensors provide data as reliable as geophones while offering significant advantages, including ease of use, lower costs, and time efficiency.

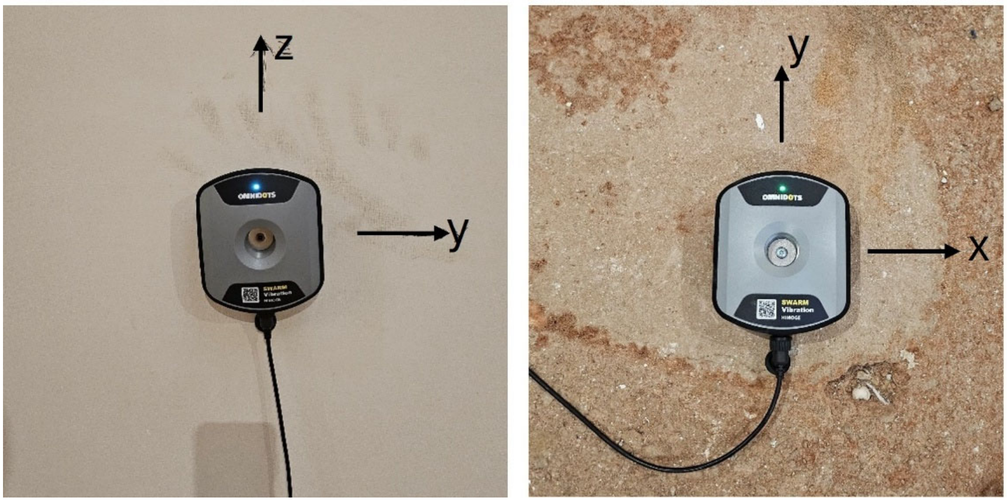

Figure 3: Triaxial velocity transducer installed on the wall (left) and podium between the sculptures (right).

3.1 Data collection and analysis

The dynamic monitoring system contains of two measuring approaches. The first strategy activates every 90 seconds to record peak particle velocity (PPV) and acceleration in the X, Y, and Z directions. Although this method does not provide a continuous time history of vibrations, it effectively monitors daily (or hourly) vibrations caused by vehicles and Metro Line 1 crosses underneath the church as well as visitors' movement, events, etc. The second strategy is event-triggered, activating only when vibrations from any source exceed a user-defined threshold of 0.15 mm/s in both horizontal and vertical directions. When a sensor detects a velocity above this limit, the system records data, capturing both a pre-trigger interval of 3 seconds and a post-trigger interval of 4 seconds. This approach provides detailed time histories of environmental and seismic vibrations whenever they surpass the specific threshold.

3.2 Transient vibrations

Short-term vibrations are infrequent and do not lead to material fatigue. Additionally, their duration is too brief to cause a significant rise in amplitude due to resonance within the structure. For this reason, the second strategy is employed to obtain the time history of vibrations due to the earthquakes, vehicles and subway trains. As mentioned previously, the sensors record vibrations that exceed the user-defined threshold of 0.15mm/s.

Figure 4 presents the time histories of the velocity response during the 2.6 and 3.4 magnitude earthquakes that struck Pozzuoli on October 13 and December 6, 2024, respectively. The earthquakes epicentre was around located 11 km away from the church, and the ground motion was induced by bradyseism activity, which is intrinsically shallow (<2 km depth) and characterized by short-duration vibrations specially for the second case as seen in Figure 4(c). Given the epicentral distance, the seismic event manifested as a short-duration shock, lasting less than 1 second. The recorded velocity time history of Figure 4(a) shows a more continuous oscillatory response with relatively small amplitude fluctuations. The response in the horizontal directions appears to be more pronounced than in the vertical direction. The motion is persistent over a longer duration (~14 seconds), representing low intensity shaking with multiple small excitations. Meanwhile, in Figure 4(c) the recorded velocity response exhibits a sudden and sharp peak, indicating a short-duration impulsive motion. The most significant velocity peak is recorded in the vertical direction, reaching approximately 0.73 mm/s, suggesting strong vertical response, almost 4 times of previous one. The horizontal components show only minor fluctuations, further confirming the dominant vertical nature of this seismic event. The shorter duration of the excitation indicates that the structure experienced a sudden impact rather than prolonged shaking. The observed velocity peak suggests that the sculpture experienced a brief but intense dynamic excitation. Furthermore, (b) and (d) indicate the Power Spectral Density (PSD) of the recorded velocity response in three orthogonal directions using the Fast Fourier Transform (FFT) given by the dominant frequency. The graphs show how the energy of the vibration is distributed across different frequencies. The dominant frequency of recorded signals for both cases are approximately close to each other. However, the energy is more distributed along the frequency for the first excitation in the vertical component (b), however, this is opposite for the second excitation when almost all the energy in vertical component is concentrated in the frequency close to 1 Hz (d).

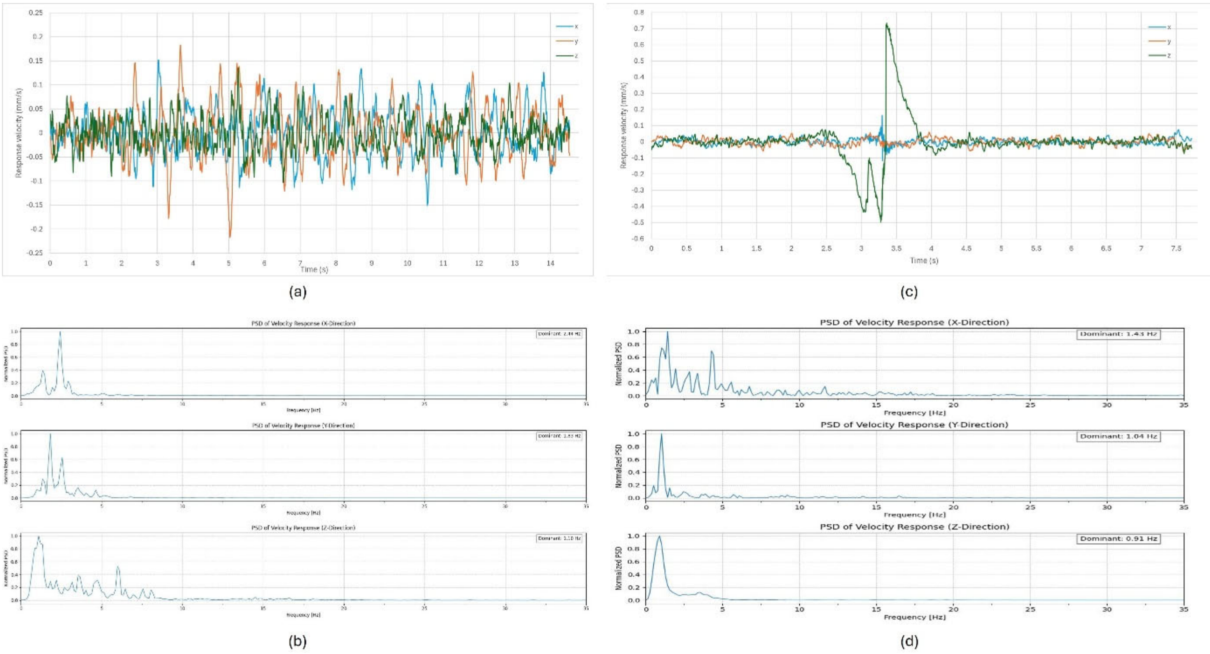

Figure 4: Recorded time history of vibration induced by M2.6 Earthquake on October 13, 2024 (a), given by its PSD and corresponding dominant frequency of each component (b), recorded time history of vibration induced by M3.4 Earthquake on December 06, 2024 (c), and its PSD with dominant frequency of each component (d).

Additionally, Figure 5 compares the vibration responses induced by vehicular traffic on two random days, through time history plots and PSD analyses. The time history plots (a, c) illustrate the recorded velocity response in three directions, showing random fluctuations with potential variations in amplitude between the two dates. The corresponding PSD plots (b, d) reveal the dominant frequency components of the vibrations, while they appear similar across both dates. The amplitude of horizontal component of velocity response time histories caused by vehicular traffic, is slightly higher than the vertical component.

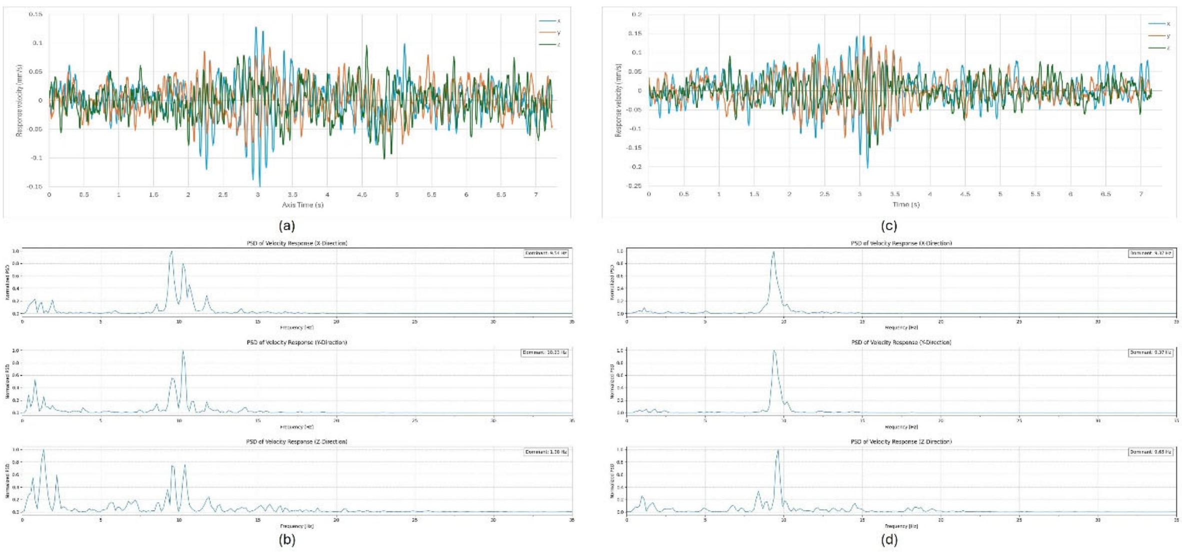

Figure 5: Recorded time history of vibration induced by vehicular traffic on November 16 2024 (a), given by its PSD and corresponding dominant frequency of each component (b), recorded time history of vibration induced by vehicular traffic on December 26 2024 (c), and its PSD with dominant frequency of each component (d).

Furthermore, two velocity response time histories of the vibration induced by Metro Line 1 crossing 50 meters away from the church building at a depth of 40 meters is indicated in Figure 6 along with their dominant frequencies. The subway induced vibration exhibits more pronounced peaks at higher frequencies compared to the ones induced by vehicular traffic. It also demonstrates that the vertical component of the two subway-induced vibrations have significantly higher amplitudes than their horizontal components.

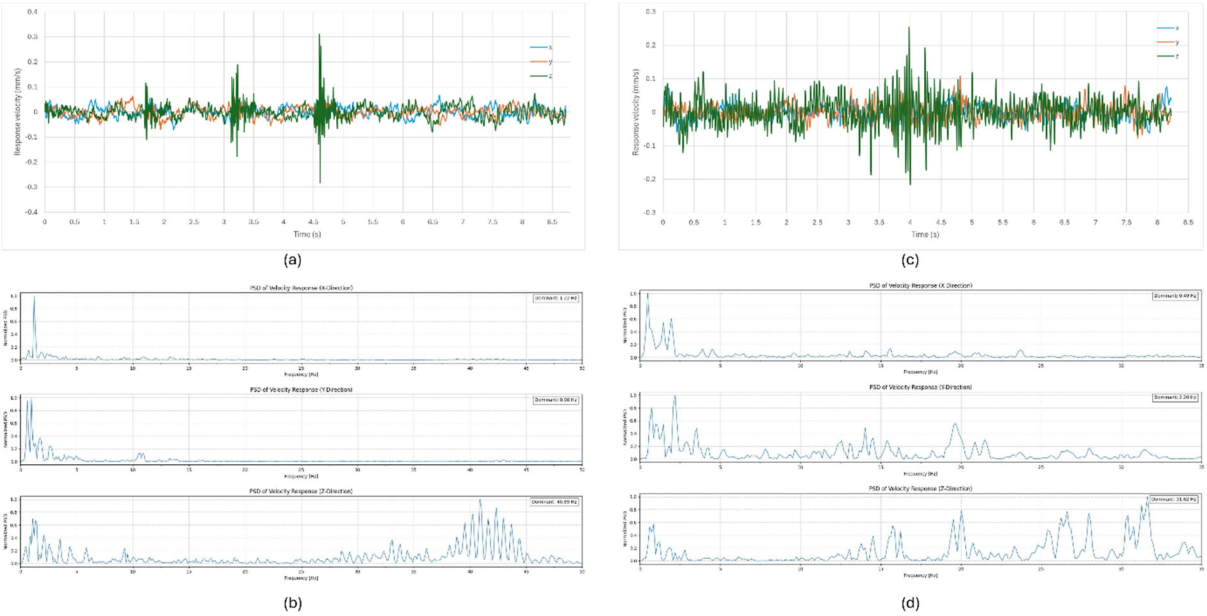

Figure 6: Recorded time history of vibration induced by subway traffic on November 19, 2024 (a), recorded time history of vibration induced by subway traffic on December 31, 2024 (c), given by their PSD with dominant frequency of each component (b), (d).

3.3 Permanent vibrations

Permanent ambient vibrations at the site originate from continuous sources such as environmental factors, microseismic activity, and human activities like walking and distant traffic. Unlike transient vibrations, which result from short-duration events such as passing vehicles or construction activities, ambient vibrations persist over time and provide insight into the dynamic behaviour of the structure. The sensors continuously record peak particle velocity every 90 seconds. Figure 7 presents the recorded PPV from September 11, 2024, to January 6, 2025, in three directional components. Most recorded values remain around 0.15 mm/s, indicating relatively low vibration levels, typical for ambient conditions. It is noteworthy that on October 6 the sensor was reinstalled from adjacent wall to the podium between the sculptures. This relocation likely influenced the recorded vibration levels, as the new position is more directly exposed to structural responses from both subway and vehicular-induced ground vibrations. Before October 6, the recorded PPV values were relatively stable with minor variations, indicating that vibrations transmitted through the adjacent wall were dampened. After the sensor relocation, slightly higher variations in PPV are observed, particularly in the vertical component, suggesting increased sensitivity to local dynamic excitations. Moreover, several spikes suggest transient events with higher intensity, likely due to localized disturbances such as vehicular and subway traffic surges, construction activities and far-field earthquakes. This shift in measurement position provides a more direct representation of the vibrations affecting the sculpture.

The distribution of points suggests that while ambient vibrations are consistent over time, occasional transient events cause momentary increases in structural response.

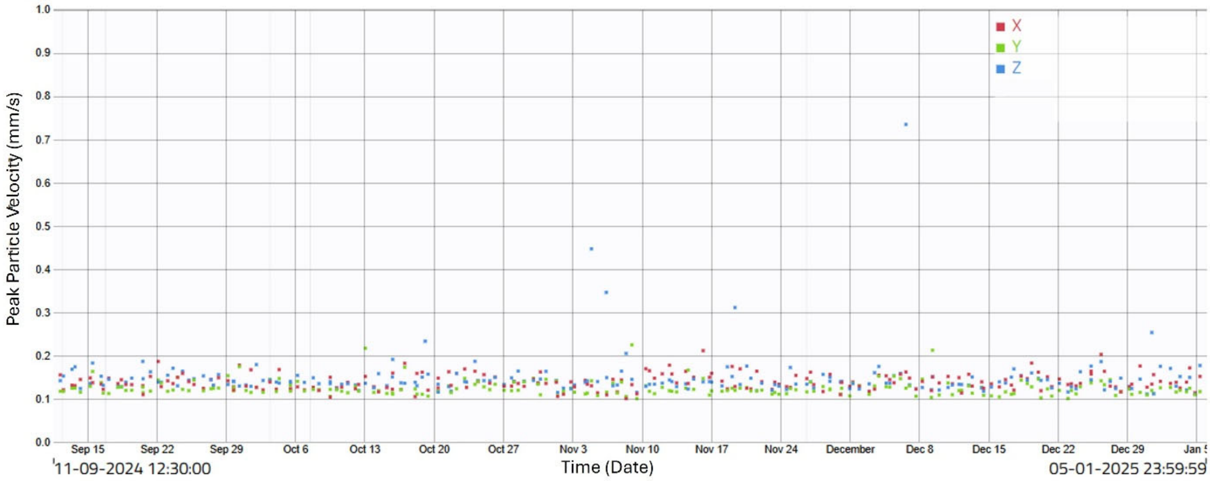

Figure 7: Continuously long-term recorded peak particle velocity.

Figure 8 meanwhile presents the distribution of PPV over dominant frequencies, offering insight into the frequency-dependent characteristics of recorded vibrations on the site. The data points, categorized by directional horizontal and vertical components, with distinct frequency clusters linked to specific vibration sources. Vibrations in the 1–3 Hz range are mainly associated with footsteps of visitors and microseismic activity due to bradyseism in Pozzuoli, reflecting low-frequency ground movements. The dominant cluster around 10 Hz is attributed to vehicular traffic, indicating its significant contribution to the structural response. At higher frequencies, particularly above 20 Hz, the recorded vibrations correspond to subway-induced excitations, with these high-frequency components being primarily governed by the vertical direction, suggesting that underground train operations generate dominant vertical accelerations. The presence of these distinct vibration sources highlights the complex dynamic environment of the monitored sculptures, where continuous ambient vibrations coexist with transient excitations from human activity, vehicular loads, and seismic occurrences. Moreover, all PPV values remain well below the safety threshold of 2mm/s.

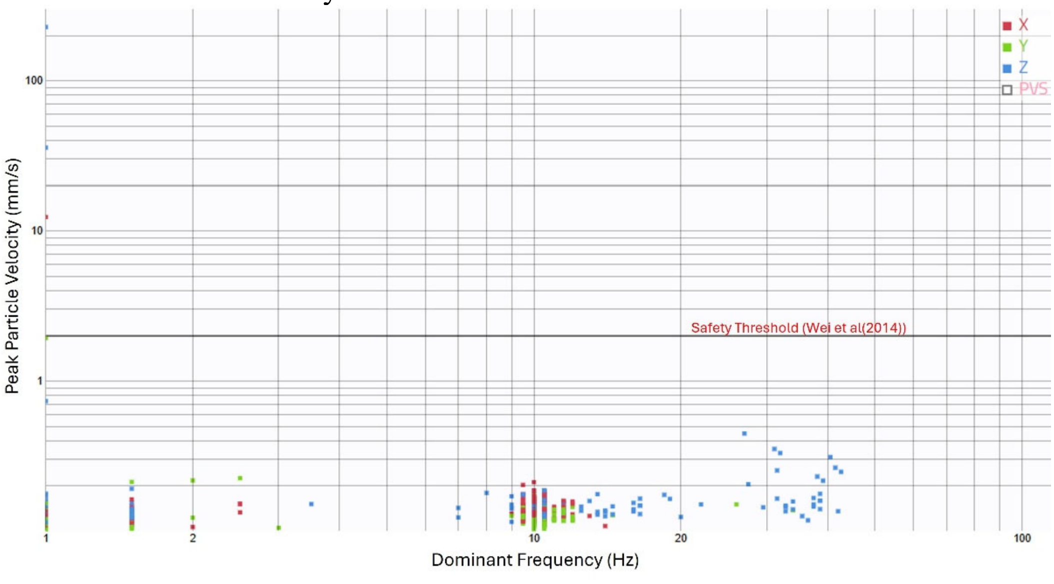

Figure 8: Distribution of recorded PPV along the frequency of vibrations for long term monitoring.

3.4 Vibration Mitigation

Although the level of ambient and occasional vibrations on the sculptural set are not significant, transferring them in other locations for temporary exhibitions, or occurrence of a huge earthquake may cause serious damage on them. Hence, reducing their response subjected to these excitations is inevitable. To mitigate the effects of dynamic excitations on sculptures, isolation techniques can be employed to reduce transmitted vibrations and potential damage. One such approach is the use of wire rope isolators, which provide flexibility and damping while accommodating multi-directional movements. These isolators consist of intertwined wire cables secured between metal end fixtures, offering high energy dissipation and corrosion resistance. Another effective strategy involves neoprene pads, which can be placed beneath the sculpture to absorb ground-induced vibrations. These materials exhibit both stiffness and damping properties, helping to decouple the sculpture from its base while maintaining stability. The selection of an appropriate isolation system depends on factors such as the sculpture's weight, material properties, and the frequency content of the dynamic loads. Further research and experimental validation are recommended to optimize these isolation techniques for cultural heritage preservation.

4 CONCLUSION

The dynamic monitoring of the 15th century sculptural group in a church in Naples, Italy has provided valuable insights into the vibration levels induced by various sources, including visitor footsteps, vehicular traffic, subway operations, and seismic activity. The results indicate that the majority of recorded vibrations remain below the widely accepted threshold of 2 mm/s, suggesting a low risk of structural damage to the sculptures. However, transient events such as nearby seismic activity and subway-induced vibrations exhibit distinct frequency characteristics, with vertical components often being more pronounced than horizontal ones. The findings highlight the importance of continuous monitoring in heritage conservation, as environmental and anthropogenic vibrations can accumulate over time, potentially leading to micro-damage or fatigue effects. Moreover, the frequency content of each vibration source recorded by the monitoring system is assessed and depicts diversity of the ambient vibration on the site. The relocation of sensors from an adjacent wall to the sculpture's podium demonstrated increased sensitivity to local dynamic excitations, further emphasizing the need for strategic sensor placement in vibration assessments.

While the recorded vibration levels do not pose an immediate threat to the sculptures, implementing additional protective measures could enhance their long-term preservation. One potential solution is the installation of isolation devices, such as wire rope isolators, beneath the sculptures. These devices can effectively absorb and mitigate shock loads, particularly during transportation for exhibitions or restoration activities. Moreover, further refinement of vibration threshold criteria specific to different types of artifacts could contribute to the development of more tailored conservation strategies.

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