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DYNAMIC MONITORING OF AN HISTORICAL MONUMENTAL BUILDING CONTAINING PRECIOUS MOBILE CULTURAL HERITAGE ARTEFACTS AND DELICATE SCIENTIFIC INSTRUMENTS

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Abstract

The Opificio delle Pietre Dure (OPD), in Florence (Italy), is an international outstanding institution founded by Medici in the year 1588 for the restauration of sculptures, paintings and commesso artefacts. Most of its scientific laboratories are located in the Fortezza da Basso, Today; the area of the Fortezza is undergoing large renovation works that deeply impact with noise and vibrations. Moreover, the Fortezza is going to be underpass by double shallow urban tunnels executed by two TBM, posing questing on the safety of artefacts and effects of induced vibrations on the delicate restauration works. For this reason, the OPD and the Department of Earth Science of the Florence University (DST) have deployed, since Sept 2023, a small seismic network for real-time monitoring of ground vibrations to support instruments operability. The analysis, performed in real-time, allows evaluating vibration intensity, frequency content and back-azimuth. Vibrations present a daily trend due to traffic and the near rail station with a constant level of about 2 µm/s from 5 a.m. to 11 p.m. Larger amplitude vibrations, mostly result from renovation works performed nearby the site, with disturbances to the scientific instruments analysis. That allowed to define a warning level (>10 µm/s), with a direct notice to selected OPD personals, that prevents operability of microscopic based restoration works. Moreover, first TBM is approaching the Fortezza subsoil in a close future. It will be interesting investigating the disturbances and possibly track TBM movement below the OPD labs.

Keywords: Cultural heritage, seismic monitoring, historical building, mobile artefacts.

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1 INTRODUCTION

As part of a general five-year Collaboration Agreement pursuant to Art. 15 L. 241/1990 signed on 9/11/2017 and renewed for another five years on 26/10/2022, on 13/09/2023 between the Opificio delle Pietre Dure of Florence (OPD) and the Department of Earth Sciences of the University of Florence (DST) a four-year supplementary agreement was stipulated (pursuant to Art. 8 of said Framework Collaboration Agreement) for the execution of geological analysis and seismic monitoring of their buildings and laboratories located in the Fortezza da Basso in Florence (Fig.1), a stronghold built by Medici in 1530 along the city-walls, in order to characterize the seismic noise level before construction work in the area and the new rail underpass [Vogiatzis, 2012; Karanikoloudis et al., 2020].

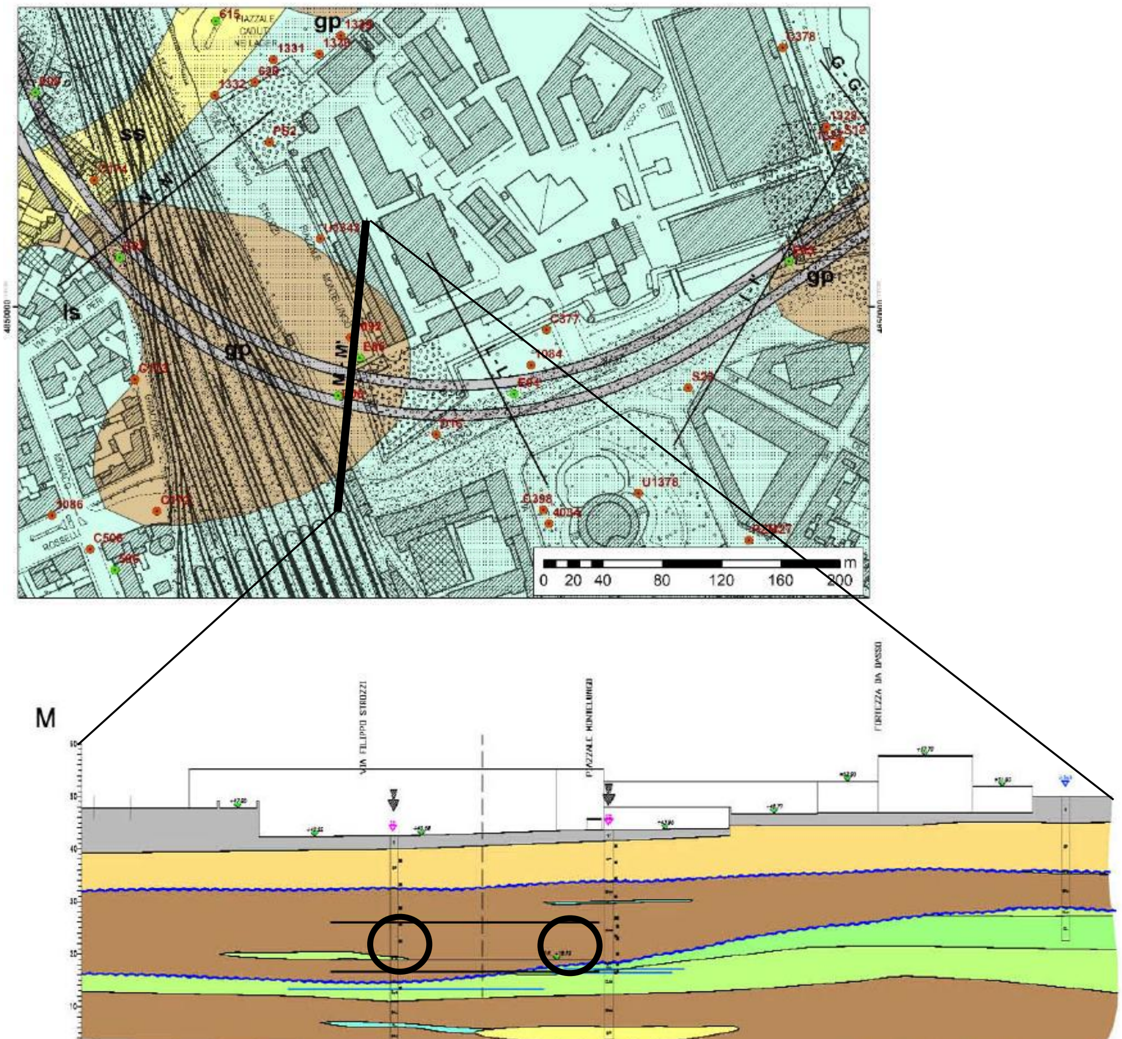

Figure 1 – Geological map of the OPD laboratory area at the Fortezza and cross section with outlined the twin new rail tunnels (elaboration M. Coli).

Such a monitoring efforts is due to the highly critical activities performed in the OPD laboratories on precious mobile cultural heritage artefacts that requires a very low seismic noise environment to perform diagnostic, restoration and conservation actions with microscopes and sensitive scientific instruments.

The aim of the research is the characterization of seismic noise, in terms of amplitude, frequency content, relative source location and characterization, and eventually the establishment of threshold levels for selected operations. The performed activity consisted into:

- Calibration and installation of 3 seismic stations.
- Data transmission via 4G data network and real-time acquisition at the DST.
- Creation of a dedicated data processing software for measuring the vibration level and defining the preferred direction of origin for the characterization of the source areas.
- Creation of a dedicated website with real-time visualization of the acquired information.
- Definition of noise level thresholds.
- Notification of threshold exceeding via email and visualization on the dedicated website.

2 MONITORING SYSTEM SPECIFICATIONS

The seismic network installed in the buildings and laboratories of OPD located in the Fortezza da Basso in Florence consists into 3 triaxial seismic stations (Fig.2) located respectively in the works deposit (OPF1), in the CNR laboratories (OPF2) and in the warehouse (OPF3).

Figure 2. Aerial photo of the OPD laboratory at the Fortezza da Basso and position of the three seismic stations installed as part of the research (elaboration E. Marchetti).

Each station consists of a Lennartz Le3D/Lite triaxial seismometer, with a sensitivity of 800 V/m/s and a natural frequency of 1 Hz and a 24-bit Lunitek ATLAS digitizer, which acquires the three components of the seismometer with a sampling step of 100 Hz and is equipped with a GPS receiver for data synchronization and a Seedlink server for data sharing. Data transmission occurs via a 4G modem. The data is acquired at the DTS using Earthworm software and archived both as daily mseed files and within a Winston database. The data is also archived locally on the ATLAS digitizers. Each station is powered directly by the OPD's electrical network.

The installation of the network began around mid-September 2023, with OPF1 and OPF2 installed as early as September 15, and was completed, with the installation of OPF3, on October 1. The presence of the OPF1 and OPF2 stations allowed to record the Marradi earthquake of 18 September 2023, with a local magnitude of 4.9, which represents the strongest event recorded within 50 km of Florence since 1919. The event, which occurred at 03:10:14 UT on 18 September, was recorded at the OPD at 03:10:21 UT with a peak amplitude of the ground vibration velocity equal to approximately 1 x 10-3 m/s (Fig.3) and provides an excellent comparison parameter with the noise level associated with human activities in the area which constitute the main source of vibration (Fig.4).

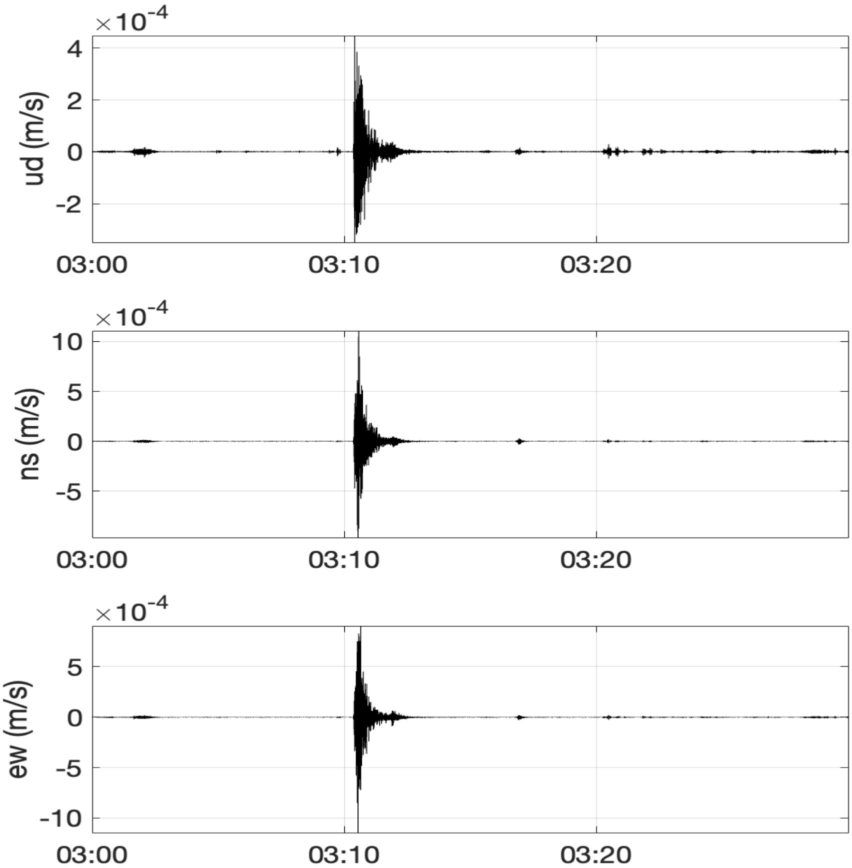

Figure 3 – Recording of the ground velocity induced by the Marradi (FI) earthquake of 18 September 2023 (Ml=4.9) in the three orthogonal components along the vertical (ud) north/south (ns) and east/west (ew) components (elaboration E. Marchetti).

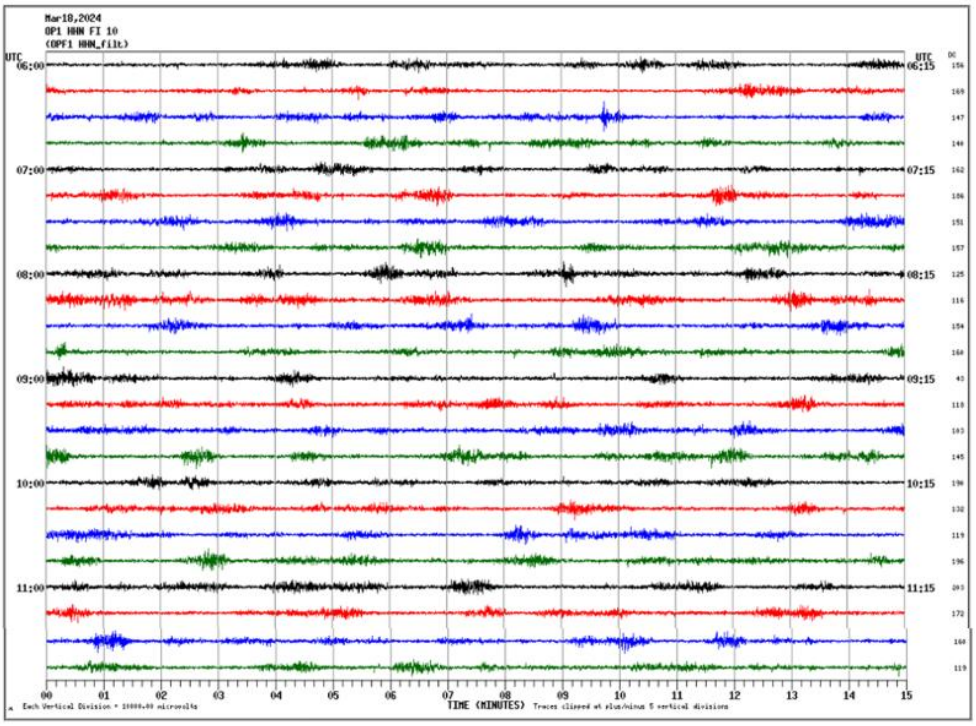

Figure 4 – Recording of the vertical component of the ground vibration velocity at station OPF1 between 6:00 UTC and 12:00 UTC on 18 March 2024. Each line corresponds to a 15-minute track (elaboration E. Marchetti).

3 MONITORING

Figure 4 shows a 6-hour trace recording the vertical component of the seismic vibration commonly induced at the OPD by ordinary and anthropic activity. Each line corresponds to a 15-minute time interval between 6:00 and 12:00 UT on March 18, 2024. Specifically, it can be observed that unlike an earthquake (Fig.3), which is characterized by a clear impulse and high amplitude, the seismic record in Figure 4 suggests the repetition of recurrent signals (6-10 events every 15 minutes) of variable amplitude and duration and with an emergent and non-impulsive waveform. Considering the 24-hour trend at the 3 stations (Fig.5), it can be observed that the seismic signal is minimal during the night hours, progressively increases in the early morning hours (from 04:00 UT), remains at a high level during the day, with a peak amplitude commonly lower than $5x10^{-5}$ m/s, and then decreases in the evening (from 20:00 UT). The emerging waveform (Fig.6a) and the 24-hour trend (Fig.5) suggest that the seismic vibration typically induced at the OPD premises is mainly associated with human activities (e.g. vehicular and railway traffic, construction works), as expected in an highly urbanized context [Riahi & Gerstoft, 2015; Meng et al., 2021].

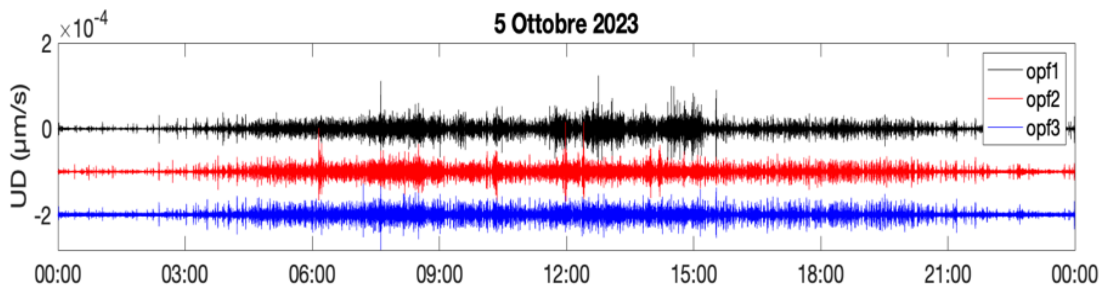

Figure 5 – Vertical component of the ground vibration velocity recorded by the three seismic stations of the OPD network for Thursday 5 October 2023 (elaboration E. Marchetti).

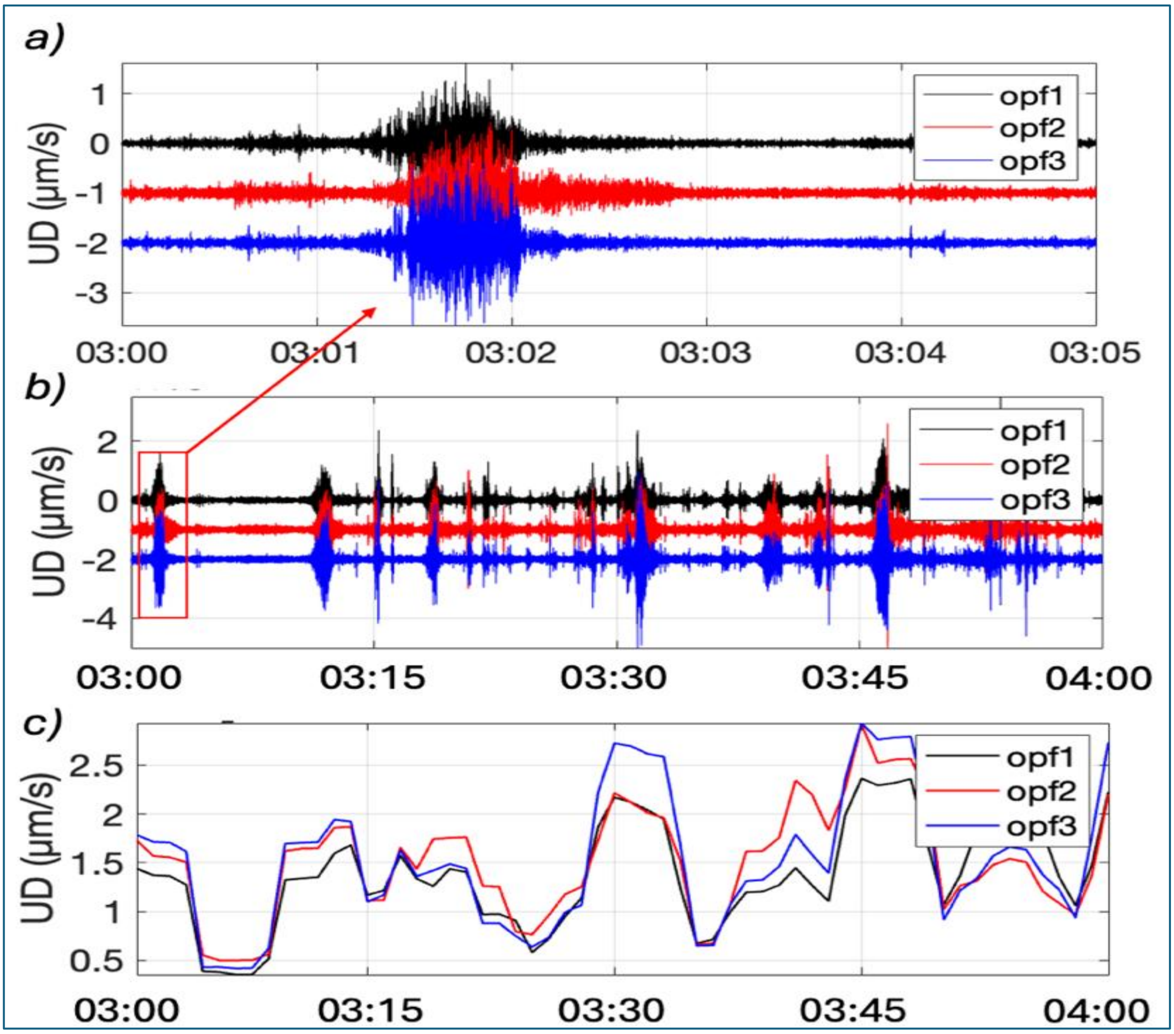

Figure 6 – Vertical component of the ground vibration velocity recorded by the three seismic stations of the OPD network for a discrete event at 03:01 on 5 October 2023 (a) and trend in an hourly interval, both in terms of signal amplitude (b) and root mean square amplitude (c) (elaboration E. Marchetti).

Considering in detail a single event recorded at the three stations (Figure 6a), it is clear that the 3 traces show analogies in terms of duration and amplitude, but it is difficult to pick the signal onset at the individual stations, therefore preventing any onset time approach for source location [Console et al., 1992]. By comparing the traces in an hourly interval, both in terms of amplitude of the seismic data (Figure 6b) and of mean squared amplitude (RMSA) calculated on a 1-minute window (Figure 6c), it is observed that the amplitude ratios at the individual stations are not constant but vary from event to event.

Seismic waves represent the propagation of an elastic deformation in the medium that occurs when there is a release of pressure inside the solid earth (earthquakes) or on the surface (traffic and human activity). The seismic wave propagates in the medium as volume waves (p and s waves) or surface waves (L and R waves) and these two types of waves are subject to a different attenuation rate with distance, which is not easy to determine a priori but which we can consider constant for the entire survey area [Lay and Wallace, 1995]. Consequently, the increase in amplitude at each station is inversely proportional to the distance from the source. Therefore, to justify the variation of the mean squared amplitude and the rations among the 3 stations of the network, it is necessary to consider sources with different positions with respect to the survey site.

3.1 Source detection

In order to characterize the seismic noise in the building and characterize the source, it is first required to define the noise level for the entire period of analysis, spanning from October 2023 to April 2025. To minimize the effects of internal activities in the factory we define the amplitude level of the signal as the minimum value among the RMSA computed for the three stations in the survey window (Fig.7).

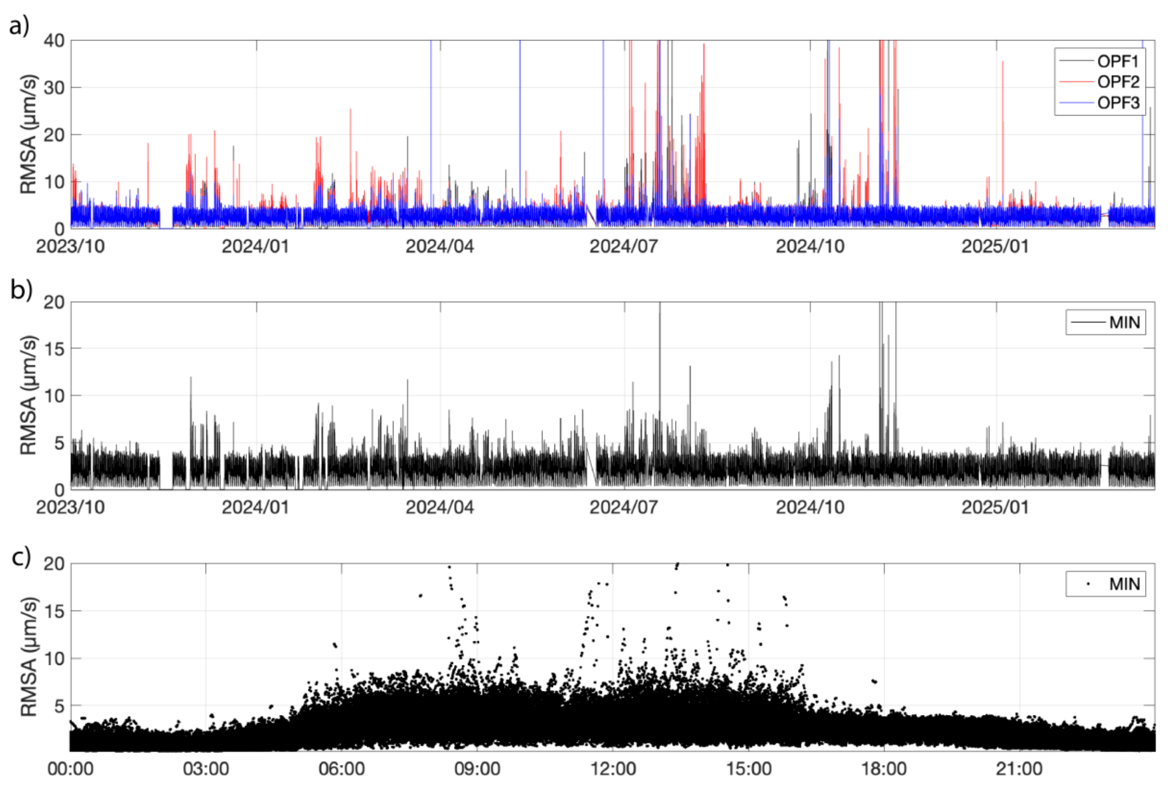

Figure 7 – Root mean square amplitude of the vertical component of the seismic signal recorded at the three stations of the network (a) and minimum value (b). Daily variation of the minimum RMSA (c).

From Figure 7, it is clear that the trend of the average quadric amplitude at the individual stations is strongly influenced by the daily trend (Figure 7c), highlights periods of increased amplitude at all stations, such October and November 2024, and shows few peaks at individual stations, like for example OPF3 in late March 2024 (Figure 7a). When computing the minimum value (Figure 7b), the first are preserved and suggest the existence of additional sources of seismic noise in the area, while the latter are removed.

This approach allows us to identify periods characterized by a significant signal increase across the entire area and exclude peak values linked to a peaks at a single station, which is instead a local phenomenon and could simply derive from steps or movements of people a short distance (meters) from the station. Moreover, the highly stable daily trend observed for the 1.5 year of analysis, allows to define a threshold value of 2.5 μm/s for low noise recorded only at night, and to define the standard noise level related to traffic and common urban activity typically below 6 μm/s.

While the minimum amplitude value (Fig. 7b) is representative of the real amplitude of the seismic signal produced at the factory by all external sources, we used the amplitude ratios to

calculate the signal backazimuth and therefore infer some source features. In particular, a procedure for calculating the direction of origin of the signal was created by exploiting the deviation between the mean square amplitude recorded at the three stations (Fig. 6c) and their mean value.
This analysis is applied on 1-minute-long data windows and calculates the ratio between the RMSA at each station with the mean value recorded across the network (Fig. 8a). The amplitude ratio for each station is multiplied with the vector that identifies the position of each station with respect to the station barycenter. The sum of the 3 vectors corresponds to the signal backazimuth that points directly to the source. The result of the analysis carried out over the period October 2023-March 2025 shows that the signal has a main direction of origin compatible with the western quadrants with respect to the survey area (Fig.8b) where rail and road traffic mainly occurs. However, intervals are observed in which the seismic signal comes from other directions.

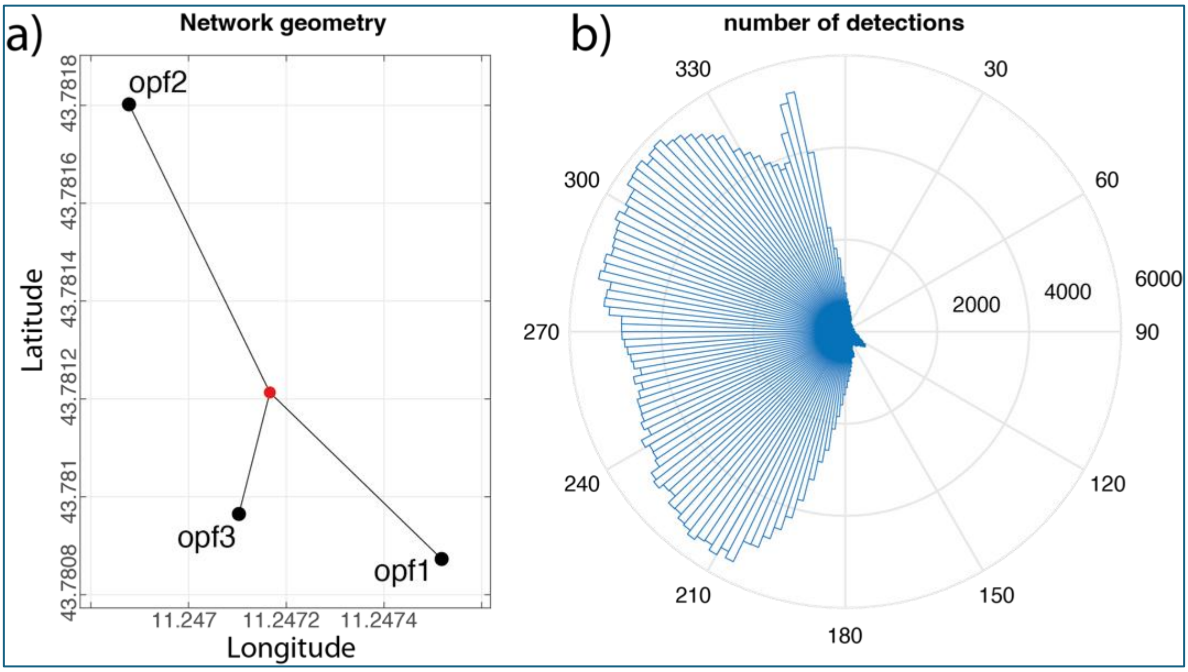

Figure 8– a) Position of the 3 stations of the network (black dots) and their barycenter (red dot). b) Azimuthal diagram showing the direction of the signal origin in the analysis period between 1 October 2023 and April 2025.

4 THRESHOLDS AND WARNING

A special focus was given to the evaluation of noise levels in order to define the attention and disturbance thresholds. The trend of the seismic noise level, over the entire investigation period, is represented in Figure 9, and shows how beyond the typical daily trend mainly linked to urban and railway traffic and which settles on an average amplitude of less than 5 µm/s (Figure 7c), periods are observed in which the noise level is significantly higher (for example July 2024).

In order to define the empirical tolerance thresholds, a page was created on the monitoring website to report periods in which the level of vibrations limited or prevented the normal performance of activities. Through the reporting system, active starting from June 2024, it is possible to indicate the time, the sector of the building and insert some notes to detail the characteristics of the problem encountered. Between 17 July 2024 and 10 October 2024, 22 reports were recorded by restoration workers, who complained of work problems due to the high level of vibrations (Figure 9). In particular, felt vibrations prevented the performance of precision activities with a microscope.

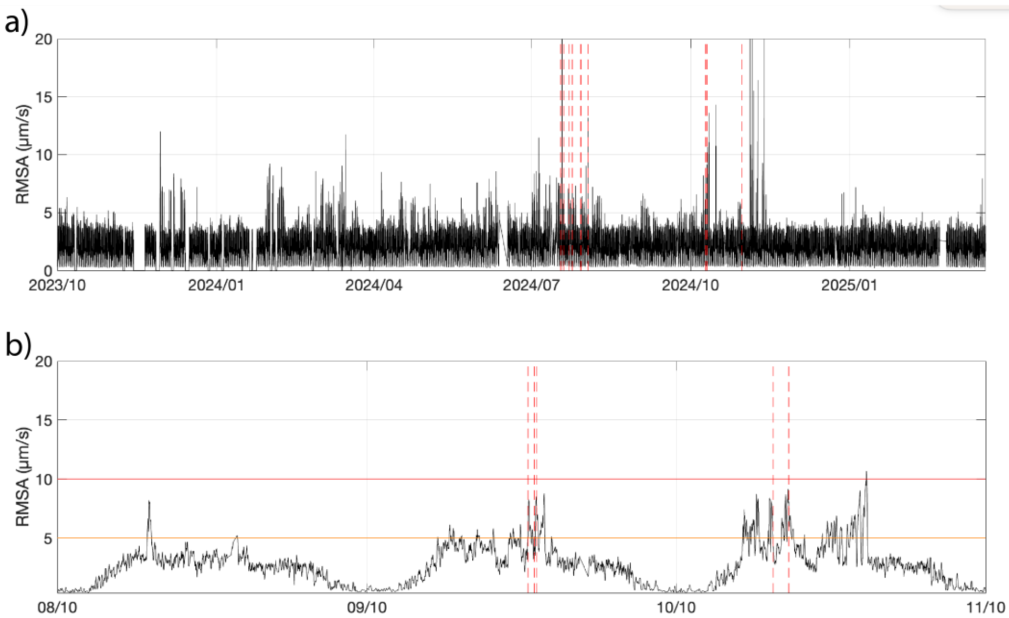

Figure 9 – Periods of increased seismic noise level (red vertical dashed line) reported by restorers during the period of analysis (a) and details of reports collected between 8-11 October 2024 (b). The horizontal lines identify the exceeding of the thresholds relating to the ordinary (5 µm/s, orange) and high (10 µm/s, red) noise level.

The reports are concentrated in two main periods, 22-24 July 2024 and 9-10 October 2024, and only when the average level of seismic noise to the structure is significantly higher than the value of 5 µm/s, a value representing the ceiling of ordinary noise, related to urban and railway traffic.

Figure 9b shows a detail of the mean square amplitude of the vertical component of the seismic signal calculated on the building in the period 8-10 October 2024, which highlights how the reports are recorded during the periods of greatest vibration amplitude. This allows us to define two thresholds, the first of 5 µm/s for exceeding the ordinary noise level (orange horizontal line in Fig.9b) and the second of 10 µm/s for reaching a high level of vibration amplitude (red horizontal line in Fig. 9b).

The analysis of the angular distribution of the seismic signal amplitude (Figure 10) shows how the western sectors are mainly associated with weak intensity signals (median around 3 µm/s) thus contributing to ordinary seismic vibrations mainly linked to urban and railway traffic, usually lower than the threshold of 5 µm/s. However, these determine the vast majority of the recorded seismic signal, recorded for over 55% of the time (Fig.10b). The most energetic signals, higher than 3 µm/s, are recorded from the eastern sectors, with peaks from specific directions (Fig.10a). These suggest the presence of important noise sources, close to the building, and mainly located within the area of the Fortezza da Basso. Although energetically important, these signals contribute to 3% of the recorded signals (Fig.10c).

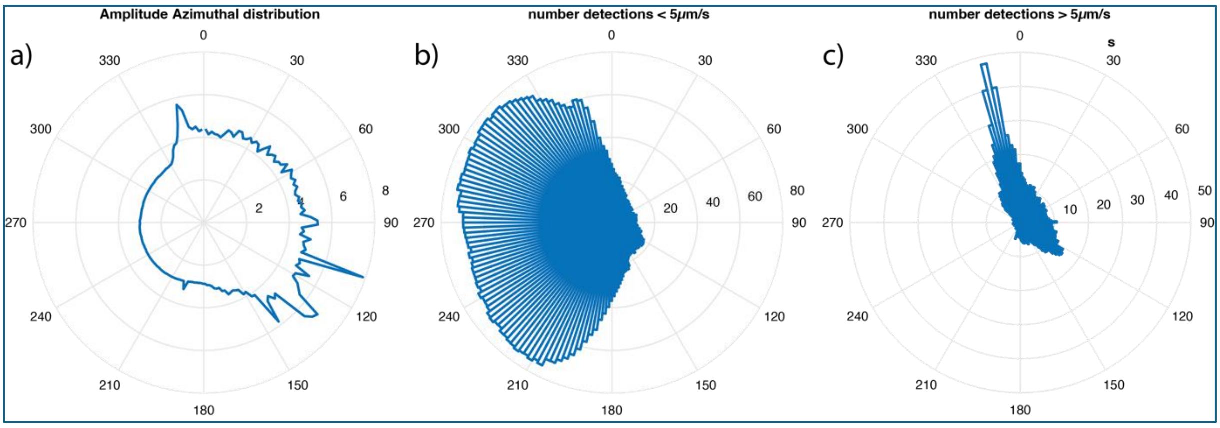

Figure 10 – Angular distribution of the mean amplitude of the seismic signal (a). Distribution of the number of analysis intervals (minutes) relating to ordinary (< 5µm/s, b) and high (> 5 µm/s, c) signals.

Following this analysis, the thresholds were also inserted into the dedicated website which shows the amplitude and direction of origin of the signal recorded in the last 48 hours (Fig.11) with the analysis performed in real-time.

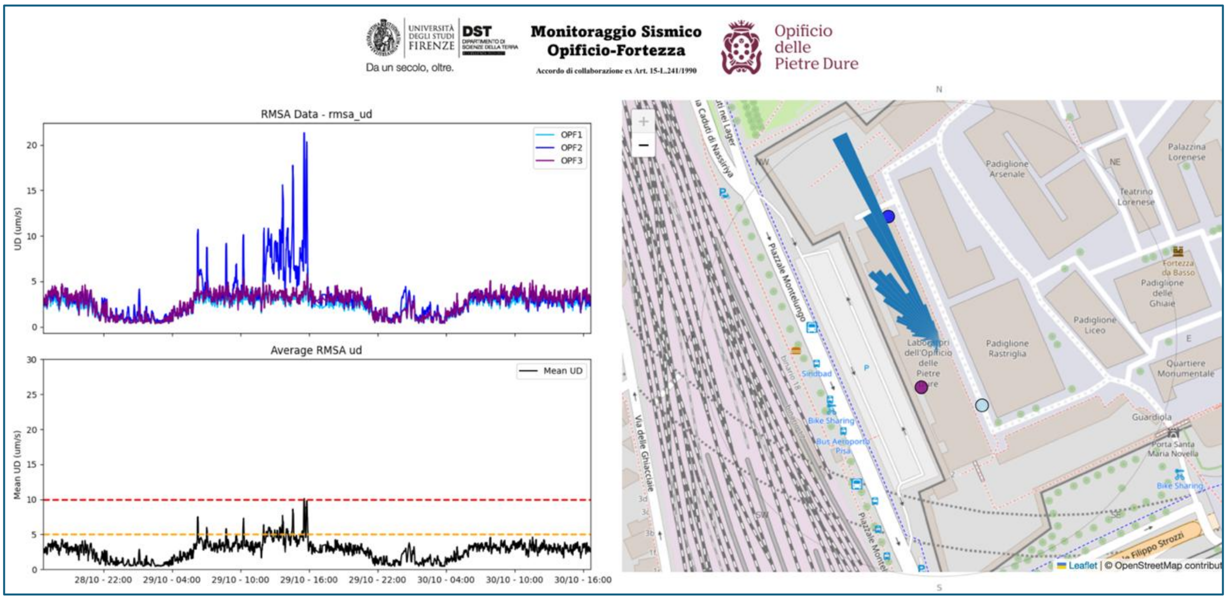

Figure 12 – Web page relating to the mean square amplitude and direction of origin of the seismic signal updated following the definition of the thresholds identified in the second semester of activity (elaboration E. Marchetti).

5 CONCLUSIONS

The activities carried out in the frame of the project have allowed us to consolidate the real-time analysis procedures of the seismic signal recorded by the three stations installed in the premises of the OPD labs located in the area of the Fortezza da Basso, to characterize the type of signal and to define, following a systematic check by the operators, the tolerance thresholds related to the restoration activities.

In particular, the angular analysis clearly shows how the ordinary activity related to urban and railway traffic, located mainly to the west of the structure, represents the main source of seismic noise at the fortress. More intense seismic vibrations are instead found as a result of human activities (construction work/excavations) located mostly in the area of the Fortezza da

Basso, to the east of the survey site. Although limited in time (about 3% of the total), these determine vibrations that limit and, in some cases, preclude particularly delicate restoration activities on the works.

Based on the distribution of the signal amplitudes, and the effects deduced from the operators' reports, we have therefore defined 2 thresholds to be applied to the mean square amplitude equal to 5 and 10 µm/s respectively. The thresholds have also been included in the figure of the mean square amplitude updated in real time on the dedicated website and available for the operators of the OPD.

With the continuation of the activities, we want to consolidate the developed monitoring procedure and guarantee the correct functioning of the system. Furthermore, the approach of the mole to the investigation site will presuppose greater attention to the investigation procedures to identify any variations that may in some way testify to possible effects on the activities of the laboratories.

Due to operating delay, we are still waiting the arrival of the two TMBs in the area under monitoring.

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