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Traffic-induced vibrations on cultural heritage in urban area: the case of Villa Farnesina in Rome

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Abstract. The study aims to analyse the vibrations induced by traffic on the Villa Farnesina in Rome. The ancient building was designed and erected by the architect Baldassarre Peruzzi and the walls, vaults and lodges were decorated with frescoes attributable to Raphael and other relevant Italian Renaissance painters. Villa Farnesina is located near the Lungotevere road, therefore it suffers the dangerous effects due to the urban traffic even with heavy vehicles passing, so much so that in the early seventies an anti-vibration paving was built. A six-month geophysical monitoring made it possible to analyse the propagation of the waves on the building, characterizing the vibration due to the current traffic level. The results show the vibration levels recorded on the different floors of the building.

1. Introduction

The Villa of Agostino Chigi - named the Farnesina when it became the property of the Farnese family - designed by the Sienese Baldassare Peruzzi and frescoed by artists of the caliber of Raphael, Sebastiano del Piombo, Sodoma and Peruzzi himself, is one of the highest expressions of the Italian Renaissance. It soon became a model throughout Europe also for its peculiar characteristics as a suburban Villa, surrounded by a garden rich in exotic plants, acting as a "hortus conclusus".

Due to the Tiber river, which laps it, the Villa has undergone several modifications over the centuries: the Loggias of Cupid and Psyche and of Galatea, located on the ground floor, and open to the garden, have been closed to remove the frescoes from adverse weather conditions and flooding of the Tiber.

Following the 17 m high flood in Rome on 28 December 1870, the regularization of the river bed at 100 m and the construction of the embankments of the Tiber were performed, also demolishing the pre-existing buildings on the river bank and a large part of the gardens to the north of the Villa Farnesina. The construction of the walls already put a strain on the resilience of the building, so much so that the Duke of Ripalta, owner of the Villa in the nineteenth century, managed to replace the pile drivers for the construction of the foundations with compressed air to prevent the strong vibrations from causing detachment of the frescoed plasters. Towards 1950 what the Duke of Ripalta had feared materialized: with the increase of heavy motorized traffic on the stretch of the Lungotevere adjacent to the Villa Farnesina, an accentuation of damage began to manifest in the shapes of the peppers that decorate the exterior of the building and in the frescoed plasters that decorate the interior.

From 1953 to 1956, by means of oscillographs, three detection campaigns were organized to reveal the vibrations which reached the Farnesina. A commission of specialists was appointed by the Accademia dei Lincei chaired by Prof. Eng. Gustavo Colonnetti, with the purpose to study the defence plan of the Farnesina. After the analysis of potential works on the Villa, in order to avoid any negative effects taking into account the geological and environmental conditions, the commission proposed an intervention directly on the Lungotevere road to reduce the vibrations impacting on the ancient building [1]. The intercepting structure took the form of an oscillating complex consisting of the mass of a new road surface resting on elastic elements: "a floating plate" which was intended to reduce the residual amplitude of vibrations to one fifth, a limit which is totally compatible with the conservation of the frescoes. The works began in August 1970 - over ten years after the proposal - thanks to the intervention of the Municipality of Rome and ended in just four months.

The structure reaches a depth of 1.65 m and extends in length along the road axis for 64.52 m with a width of 13.50 m. The carriageway was divided along the axis of the road into two independent halves, each of which is an oscillating monolithic block weighing about 400 tons resting on just over 1000 rubber pads. At the two heads, to avoid the jolt of the vehicles where the new elastic structure meets the old static ballast, a common bridge joint 2 meters long was inserted. This was then a sturdy reinforced concrete plate connected on one side with a hinge to the elastic structure oscillating and, on the other hand, matching the old roadbed through a bitumen cushion.

This was the first case in Europe (and beyond) of renovating a road to safeguard a monument damaged by today's heavy traffic.

Both for the alluvial nature of the foundation soil and for the construction of the river banks (and for the consequent raising of the aquifer), the building still continues to undergo, in its various parts, progressive micro-deformations as a result of which, inevitably, micro-cracks are produced both on the paintings and in the walls.

The research project underway at the Villa Farnesina by INGV has precisely the purpose of measuring the effect of vibrations nowadays, as a result of increased vehicular traffic.

2. Material and Methods

A temporary seismic network was deployed within and around the Villa Farnesina between October 2020 and March 2021, in order to record continuously the ambient vibrations. The network was designed to investigate the effects on the Villa, in terms of vibrations, induced from vehicular traffic both on the Lungotevere and Via della Lungara road. The first of these two road represents the main source of noise being one of the most important thoroughfares crossing the historic centre of Rome and, then, characterized by passing even of heavy vehicles.

The network was constituted by ten seismic stations: two in the garden at the ground level on the Lungotevere side (T1184 in Figure 1a) and on the opposite one near Via della Lungara (T1186 in Figure 1a); two in the basement floor, also here on both sides (T1192 and T1189 in Figure 1a); (iii) three on the first floor (T1191, T1181, T1188 in Figure 1b); three on the second floor (T1190, T1182, T1185 in Figure 1c).

It should be noted that particular attention has been payed to monitor the Loggia of Galatea, which hosts the famous fresco of Raphael. In fact, before the realisation of the Colonnetti project, the loggia suffered detachments of the frescoed plaster both during the second half of 19th century, when deleterious pile drivers had to be replaced by air canisters during the construction of the Tiber embankments [2], and the second half of the 20th century due to increase of the urban traffic, so that the director of the Central Institute of Restoration decided to put nylon nets under the vaults [2]. To analyse how the waves propagate on the different levels of the building, three stations were placed along the vertical that crosses the loggia: in the basement (T1192), on the floor (T1191) and above the vault (T1192), in addition to that installed in the garden on the same side (T1184). The other sensors were placed in correspondence of the Loggia of Cupid & Psyche and on the opposite side of the Villa, in order to assess how the vibrations decrease moving away from the main source.

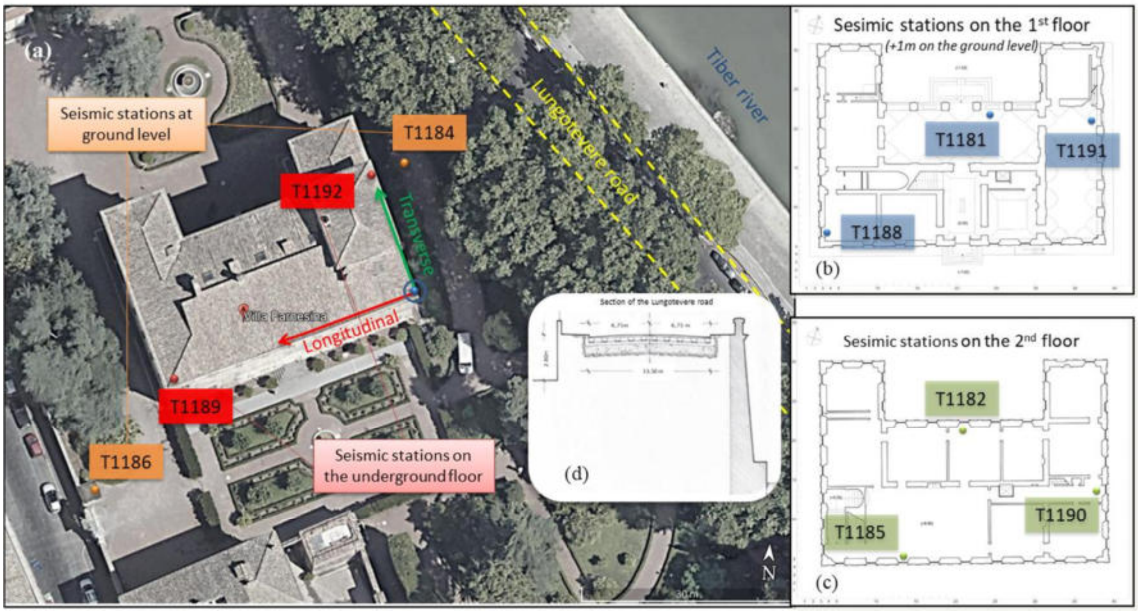

Figure 1 Villa Farnesina respect to the Lungotevere road and the Tiber river (by Google Earth©). Arrangement of the seismic network: sensors at ground level (orange circles in fig.a), at the underground floor (red circle in fig.a), on the 1st floor (blue circles in fig.b) and 2nd floor (green circles in fig.c) overlapped to the floor plans (modified by [3]). Section of the road structure suggested by Colonnetti to dampen vibrations and the wall embankment on the Tiber river (fig.d modified by [4]).

The stations were composed by CENTAUR digitizers [5], each equipped with TRILLIUM broadband seismometer [6] and TITAN accelerometer [7]. Time histories were recorded in the three orthogonal directions oriented along the north-south, east-west and up-down and the data was sampled at 500Hz using 24-bit analog-to-digital converters. Time synchronism was assured by the embedded GPS system at each station (cf. [8]). A local Wireless network was implemented for the data transmission thanks to a set of antennas, which allowed connecting the stations to the internet line made available by the *Academia dei Lincei*. In this way, the recordings by seismic stations were transmitted in real-time to the server located in the Cultural Heritage Laboratory of the INGV headquarter of Rende.

In order to analyse the traffic-induced vibrations both time and frequency-domain analysis were carried out. The presented article describes preliminary results obtained by 24-hours recordings on the October 26th, 2020. The horizontal time-histories were preliminary rotated along the two main orthogonal directions of the building (longitudinal and transverse). The velocity values are plotted in time-domain to analyse the particle motion; whereas, statistical analyses were performed in the frequency-domain by mean of the Power Spectral Density (PSD), in order to describe how the energy is distributed over the frequency content. The PSDs were obtained by processing the recorded signals through 250s-length time windows in the range 0.1-50Hz (with 256 frequency steps in logarithmic scale), then the mean values and standard deviations were calculated on the daily recordings.

3. Results and Discussion

In Figure 2 the PSDs are plotted for the two sites at the ground level located outside the building. In the charts of the figure, as those in the next one, the blue, red and green curves represent the vertical, longitudinal and transverse components (cf. Figure 1), respectively. A significant energy in the frequency range between 10 and 30Hz is showed on the site near the Lungotevere, with the maximum amplitudes in the transverse direction almost parallel to the same road. This frequency content identifies the vibrations induced by urban traffic. In fact, an overlapping main frequency content was detected by Colonnetti, following the impact tests carried out by the Saga Company between 1953 and 1956 in order to characterize the vibrations due to the traffic on the Lungotevere. It should be highlighted that the amplitude in the same frequency range is an order of magnitude lower for the station on the Via della Lungara side.

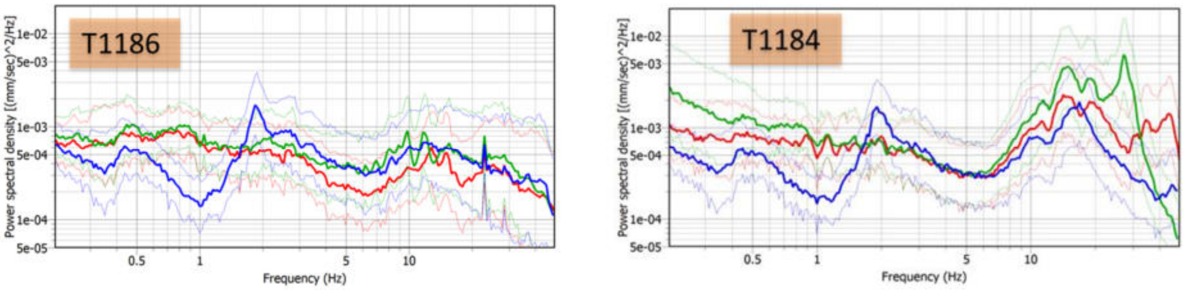

Figure 2 Power spectral density obtained from daily recording by the sismometers at ground level: on Via della Lungara (T1186) and the Lungotevere side (T1184). Blue, red and green curves are vertical, longitudinal and transverse components (cf. Figure 1), respectively.

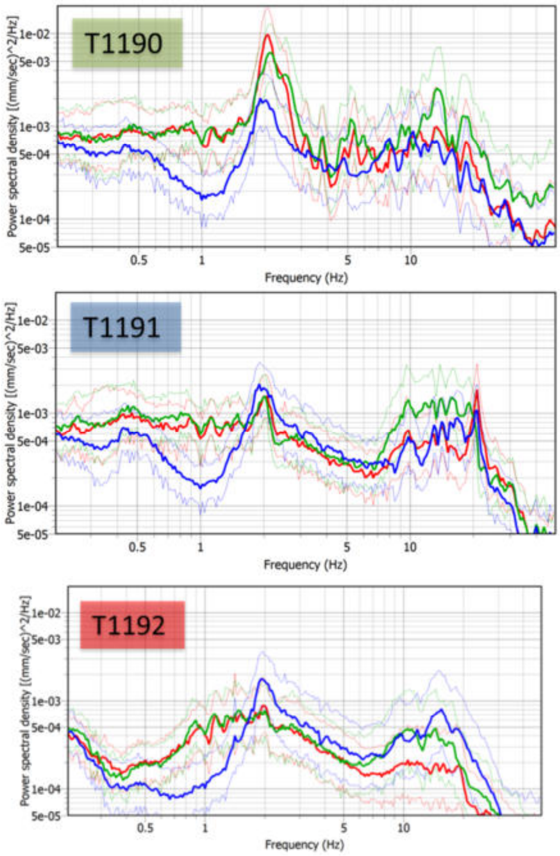

Figure 3 Power spectral density obtained from daily recording by the sismometers inside Villa Farnesina along the vertical that crosses the Loggia of Galatea: in the basement (T1192), on the 1st floor (T1191) and on the 2nd floor (T1192). Blue, red and green curves are vertical, longitudinal and transverse components (cf. Figure 1), respectively.

The PSDs show that the energy content mainly related to the traffic is attenuated inside the Villa (cf. Figure 3): this is still detectable in the range between 10-20Hz, although with lower power amplitudes, and significantly decrease moving towards greater frequencies. Moreover, the amplitude values are smaller in the basement than on the upper floors of the building.

Furthermore, the horizontal components show power peaks in the frequency content around 2Hz (Figure 3), which increase from the basement to the 2nd floor. Two peaks, more in detail, are detectable by the power curves at about 2.15Hz and 2.52Hz - as also confirmed by the other recordings inside the Villa -, which probably represent natural frequencies related to the structural modes of the building.

It should be noted that a power peak around 2Hz persists also in the vertical components of all recordings both inside and outside the Villa. The power amplitudes related to this frequency content are practically comparable in all sites and probably related to the embankment wall on the Tiber river [9], however a specific investigation would be useful to confirm this.

Given the large collection of recordings, the calculation of the PSD was repeated for each of the archived traces, thus obtaining numerous PSDs of the environmental noise relating to the measurement points and, then, the Probability Density Functions (PDFs) (Figure 4).

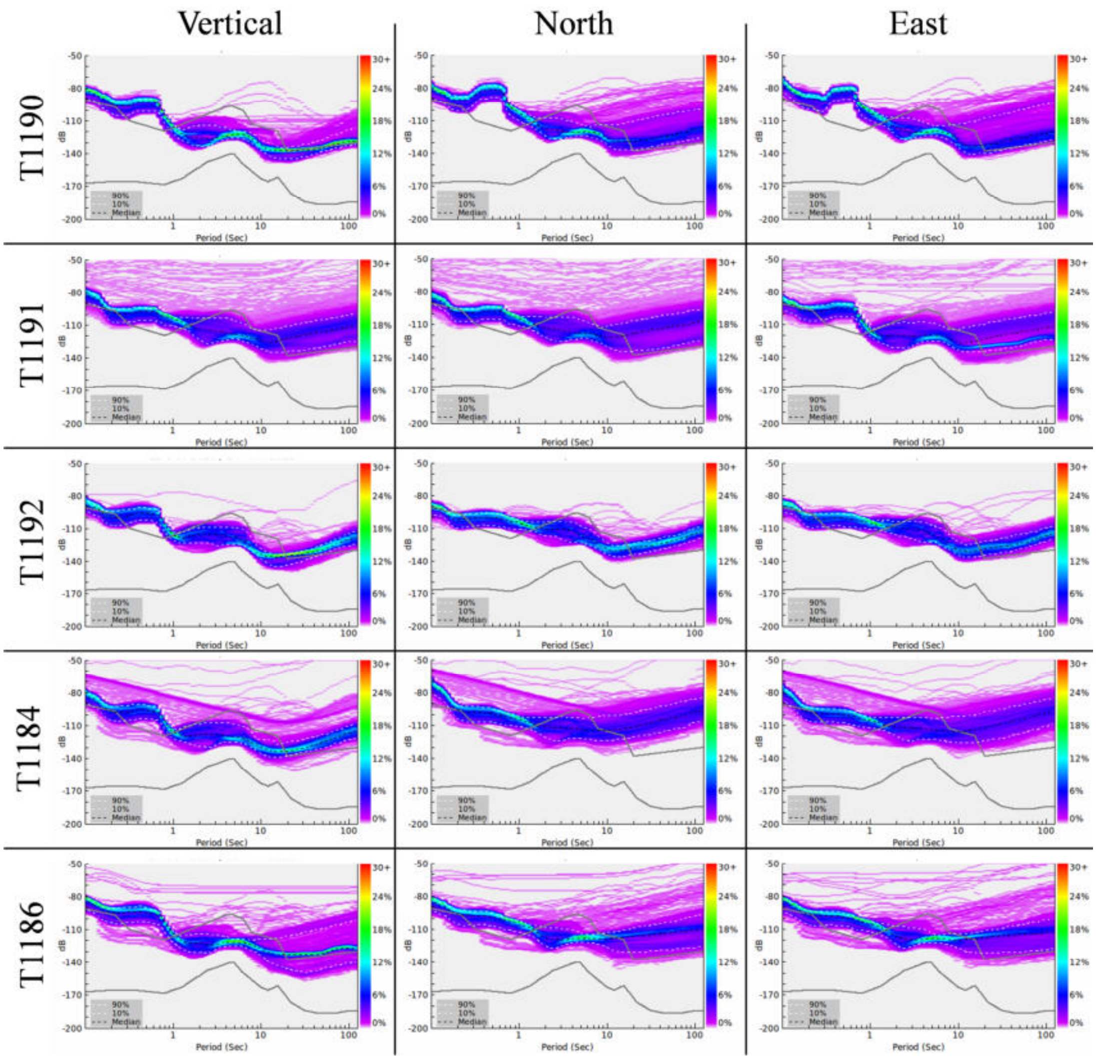

Figure 4 Probability Density Functions (PDF) inside and outside the Villa.

The PDF describes, at each frequency of the spectrum, the probability distribution of the spectral ordinates of the PSD, representing a statistic of the noise levels at each recording site. The curves relating to the New High Noise Model (NHNM) and the New Low Noise Model (NLNM) were used as references of the noise values, representing respectively the upper and lower limits of the global noise model proposed by [10]. In addition, 10th and 90th percentile are reported in the charts. The

PDFs show a relative dispersion in the two external sites and at the 1st level of the Villa; whereas, on the 2nd level and at the basement the curves are more defined in the frequency range 0.2-10Hz, as a filtering due to the structure. Once again, the peak around to 2Hz is detectable in the horizontal components, increasing from the basement towards the 2nd floor.

By analysing data in the time-domain, a peak particle motion lower than 1.2mm/s is encountered by unfiltered recordings both in the garden and inside the building, however these values are below the threshold (2-3mm/s) provided by the international standards and recommendations for historic building and archaeological sites.

4. Conclusions

The geophysical monitoring allowed assessing the vibration levels inside and outside the Villa Farnesina. The comparison between recordings in the garden and on the different floors of the building, in terms of power spectral densities, shows the decay of the energy related to the current traffic on the Lungotevere road. In addition, the results seems to indicate natural frequencies (around 2Hz) related to the structural modes of the historic building. At the end, the historic anti-vibration paving and the new methodologies and materials applied in the road construction seem to have made it possible to limit the levels of vibration; in fact, the preliminary results show the peak particle motion significantly lower to the threshold proposed by the international standards. Nevertheless, in the next analyses the entire recording period (from October 2020 to March 2021) will be considered.

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