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Analysis of hypogea environments based on ambient vibration data: application to a case study on the Palatine hill

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***Abstract* – We analyzed ambient vibration data, to rapidly identify the seismic response of an hypogea environment. The study area, is located on the Palatine hill and it is part of the Domus Tiberiana, originally built by Nero emperor. The underground cavities threaten the preservation of this important cultural asset. We used different techniques, including Horizontal to Vertical Spectral Ratio (HVSR), Power Spectral density (PSD) and Cross-Power Spectral Density (CPSD) analyses of the signals. The results demonstrated that noise measurements may be very effective for a rapid screening of cultural heritage sites and contribute to their seismic protection, by allowing for detailed identification of spatial variation of ground motions. Data was acquired in the framework of the CALIGOLA project, funded by the Lazio Region and the Italian Ministry for Research for the Technological District for new technologies.**

I. INTRODUCTION

Noise measurements are frequently used to estimate the main parameters which describe the structural dynamic response, namely the fundamental frequency of vibrations [1] or its inverse, the fundamental period.

The Italian guidelines for the assessment and reduction of seismic risk for cultural heritage [2] clearly indicate that the first vibration period T_1 of a predominantly vertically developed structure can be assessed through noise measurements.

Thus, numerous approaches have been proposed to extract these frequencies. The more classic approach is based on the calculation of the HVSR spectral ratio [3] and on the relationship between Horizontal to Horizontal (HH) components. Unfortunately, these techniques have some disadvantages, such as the difficulty of distinguishing frequencies for the natural systems which have very close modes.

Furthermore, noise measurements can be considered a very useful tool screening for cognitive purposes when soil-structure interaction is expected or subsoil conditions and any eventual observed spatial variation of motion need better knowledge. Literature works (e.g.: [4]) have shown the potential of being able to detect velocity inversions (such as the decrease in velocity induced by the presence of a cavity) from the HVSR curve. Noise measurements nearby underground cavities generally show HVSR values of less than one unit due to the higher energy of the vertical component compared to the horizontal components.

Evidently, a considerable improvement in terms of number of results may come from deployments of noise measurements in arrays, where sensors are in simultaneous acquisition. For structural health monitoring purposes, sensors are generally arranged on different levels of the same vertical. As will be detailed later, an adaptation of this overall framework to two levels, is used in this study.

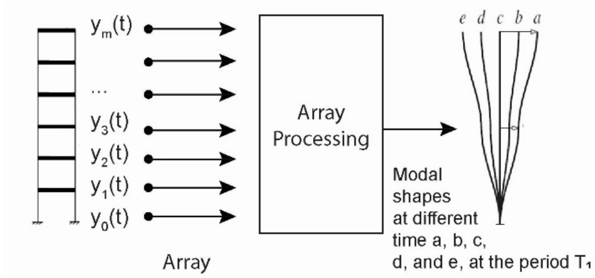

Fig. 1 Theoretically layout of a collection of sensors deployed in array and schematic representation of the output (modified after [5]*).*

As shown by Carini and Rocha [6], this layout allows the application of innovative processing techniques which can have the objective to estimate the modal shapes, and provide indications on the dynamic model of the structure. Todays dissemination of the noise measurements as method for structural health monitoring, and screening for cognitive purposes and in maintenance controls, is even

greater due to the recent evolution and diffusion of seismic nodal acquisition systems [7] and fiber optic sensing techniques [8], which allow the creation of distributed networks of sensors.
Thus, the application on the current structure might represent the opportunity for exporting the methodology to other similar hypogea environments.

II. STUDY AREA

The study area, called central Cryptoporticus and indicated by a white rectangle in Fig. 2, is part of the Palatine hill and the Archaeological central area of Rome. Palatine hill is the site of the primitive roman settlement, that became over time the exclusive residence of the highest nobility and then of the roman emperors. The study area is flanked on the East by the Colosseum and on the West by the Circus Maximus and the Tiber River.

In Fig.3 a closer view of the case study is reported, zooming internally on the hypogea environments of the central Cryptoporticus. The Cryptoporticus is part of an articulated architectural sector pertaining to the Domus Tiberiana, the first dynastic palace originally built by Nero emperor after the fire of 64 AD (Anno Domini).

In the periods following Nero emperor, this complex site experimented several substantial changes aimed at adapting the palace to the renewed administrative needs, but in the medieval period the area was gradually abandoned and it suffered a period of decay until the Farnese family created the Horti gardens in 1564.

Following the acquisition of the Horti Farnesiani by Napoleon III, Emperor of the French, in 1861, the first systematic investigations began in 1862 by Pietro Rosa, followed by excavations. These excavations made it possible to bring to light the underground environments by freeing them from the backfilling in at least three of the four sides of the Cryptoporticus.

The study area is seriously affected by geological and anthropic hazards. The main factor is likely the presence of cavities and tunnels, artificial, that constitute real underground networks continuing for several meters in the hill. Especially where cavities are dug close to the surface, they may cause the collapse of the foundations of the above structures.

The presence of cavities deeply affects the stability of the study area as demonstrated in the proximity (i.e. in the Domus Flavia [9]) and by the roof of the SW side of the Central Cryptoporticus. This latter is affected by significant deformations.

Also, ambient vibrations arising from man-made sources, including construction activities, vehicle and rail traffic may interfere with the surrounding built environment contributing to the increase of the overall vulnerability of area.

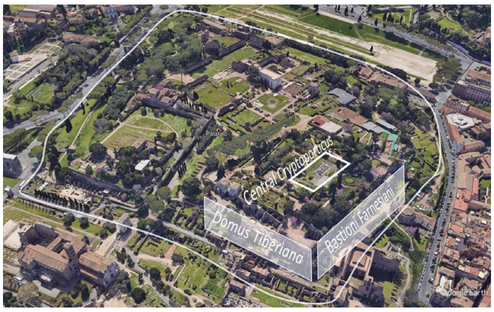

Fig. 2. *View from North of the Palatine hill with localization of the study area*

Fig. 3. Internal view of the central Cryptoporticus

III. DATASET DESCRIPTION AND PROCESSING

Noise measurements data were acquired to have a detailed picture of the state of health of the cultural heritage. Thirty-five noise measurements were carried out for this purpose (see Table 1).

SS02 SARA velocimetric sensors with a cut-off frequency of 0.2 Hz, connected to six-channels SL06 SARA data loggers were used.
To obtain the data, we used seven seismic stations which recorded simultaneously ambient vibrations (noise), according to different configurations (for brevity C. in Table 1). These configurations were designed in order to investigate the different sectors of the Cryptoporticus and all the necessary data.

The measurements were arranged on the two explorable levels: the ground (i.e. the roof of the four galleries defining the Cryptoporticus) and the hypogea (i.e. the floor of the three excavated sides of the Cryptoporticus).

In Fig. 4 two example views of the different deployments, on the roof and on the floor, are reported.

Fig. 5 plots with different colors the location of the measurements carried out inside and outside the galleries. For sake of clearness, the four investigated sectors are numbered clockwise from 1 to 4. Furthermore, measurements may be divided into three groups:

- group 1: (sector 2nd) measurements carried out on the surface (from CAL26 to CAL32) with the aim of characterizing the unexcavated side;
- group 2 (part of the 1st sector and 3th and 4th sectors): measurements carried out jointly in underground environments and on the surface (from CAL01 to CAL25) aimed at defining the mode shapes and dynamically identifying the response of the artifacts;
- group 3 (part of the 1st sector) measurements carried out only on the ground (from CAL33 to CAL35) with the aim of characterizing the NE side, not accessible from inside, for the investigation of problems related to the presence of cavities.

Surface noise measurements from CAL26 to CAL35 were performed for a minimum duration of 1 hour.

The noise measurements made for modal characterization were acquired for a longer time (about 10 hours).

Table 1. Chronological table of the noise acquisitions

ID	C.	NAME	START TIME	STOP TIME
1	1	CAL01	18.10.2023 10:40	19.10.2023 06:46
2	1	CAL02	18.10.2023 10:40	19.10.2023 06:46
3	1	CAL03	18.10.2023 10:40	19.10.2023 06:46
4	1	CAL04	18.10.2023 10:40	19.10.2023 06:46
5	1	CAL05	18.10.2023 10:40	19.10.2023 06:46
6	1	CAL06	18.10.2023 10:40	19.10.2023 06:46
7	1	CAL07	18.10.2023 10:40	19.10.2023 06:46
8	2	CAL08	19.10.2023 10:24	20.10.2023 07:24
9	2	CAL09	19.10.2023 10:24	20.10.2023 07:24
10	2	CAL10	19.10.2023 10:24	20.10.2023 07:24
11	2	CAL11	19.10.2023 10:24	20.10.2023 07:24
12	2	CAL12	19.10.2023 10:24	20.10.2023 07:24
13	2	CAL13	19.10.2023 10:24	22.10.2023 11:06
14	2	CAL14	19.10.2023 10:24	20.10.2023 07:24
15	2	CAL15	19.10.2023 10:24	20.10.2023 07:24
16	3	CAL16	20.10.2023 10:10	21.10.2023 07:00
17	3	CAL17	20.10.2023 10:10	21.10.2023 07:00
18	3	CAL18	20.10.2023 10:10	21.10.2023 07:00
19	3	CAL19	20.10.2023 10:10	21.10.2023 07:00
20	3	CAL20	20.10.2023 10:10	21.10.2023 07:00
21	4	CAL21	21.10.2023 15:44	22.10.2023 06:38
22	4	CAL22	21.10.2023 15:44	22.10.2023 06:38
23	4	CAL23	21.10.2023 15:44	22.10.2023 06:38
24	4	CAL24	21.10.2023 15:44	22.10.2023 06:38
25	4	CAL25	21.10.2023 15:44	22.10.2023 06:38
26	5	CAL26	22.10.2023 08:52	22.10.2023 10:35
27	5	CAL27	22.10.2023 08:52	22.10.2023 10:35
28	5	CAL28	22.10.2023 08:52	22.10.2023 10:35
29	5	CAL29	22.10.2023 08:52	22.10.2023 10:35
30	5	CAL30	22.10.2023 08:52	22.10.2023 10:35
31	5	CAL31	22.10.2023 08:52	22.10.2023 10:35
32	5	CAL32	22.10.2023 08:52	22.10.2023 10:35
33	5	CAL33	22.10.2023 11:06	22.10.2023 12:06
34	5	CAL34	22.10.2023 11:06	22.10.2023 12:06
35	5	CAL35	22.10.2023 11:06	22.10.2023 12:06

To avoid transient noise, for each configuration, the stationary portion of the entire signal was selected using a variable number of windows with a 50 seconds time length. Further details can be found in Gaudiosi et al. [10], where close measurements on ground were preliminary compared.

Firstly, in addition to the HVSR spectral ratios, each measurement was individually analyzed in terms of Fourier spectrum of the individual components and polarization of the signal.

Then, we computed the power spectral density function

(PSD) by using a non-parametric method named in the scientific literature as Welch's method [11].

Welch's method is based on dividing the signal into M segments, each of length N. Each segment is windowed before the DFT (Discrete Fourier Transform) is calculated, and the modified periodogram (magnitude squared of the windowed DFT) is averaged for each frequency line. Usually, the time windows are overlapped with the aim of decreasing the random error of the PSD estimate.

We divided the signal into sections of length of 600s, windowed with a Hamming window with 50% overlap between adjoining sections for evaluating the spectrum at 4096 frequencies in the range 0-100 Hz (df=0.05 Hz).

The comparison between two signals can also be made in terms of cross-correlation CPSD. This latter provides information regarding the coherence of the harmonics of the signal.

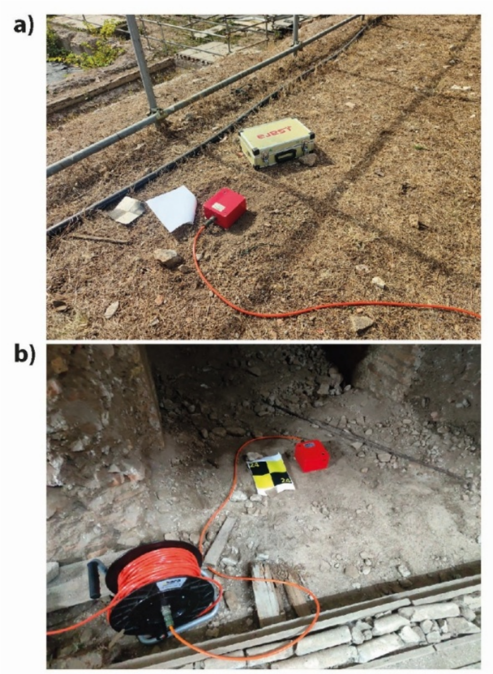

Fig. 4. Velocimetric sensors views: a) measurement on ground; b) measurement in hypogea environment. Instrumentation is capable of detecting the three components of motion in a wide range of frequencies and with high dynamics.

The expected impacts of hypogea cavities on the environmental noise measurements were previously analyzed in [10].

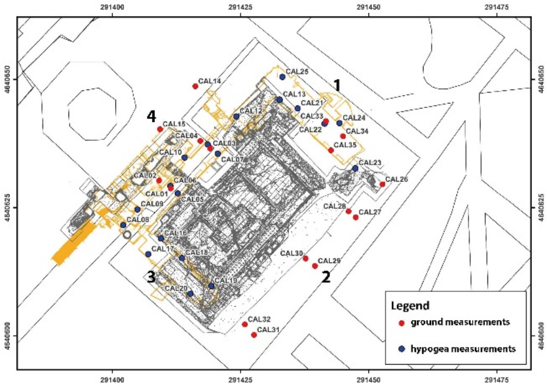

Fig. 5. Schematic representation of the study area with indication of the position of the instruments (if on ground - blue circles; or in hypogea - red circles) and stations names. Yellow lines represent the hypogea environment perimeter, while the black lines are the map of the artifacts on the ground of the central Cryptoporticus.

IV. RESULTS

Main results were obtained individually from each measurement in terms of the Fourier spectrum of the individual components, HVSR spectral ratios and polarization of the signal.

Differences were found among measurements carried out along the long-not excavated side (sector 2nd in Fig.5) and the parallel underground side (sector 4th in Fig.5) and between sector 1st and 4th.

We used power spectral density PSD and CPSD computation to corroborate these results and to fix the natural frequencies of the system.

For clarity, only results for the vertical in correspondence of CAL01 and CAL02 along the 4th sector will be shown. Fig. 6 shows the perspective drawing of this vertical of investigation with indication of the position of closer measurements: CAL01, CAL02, CAL05 and CAL06.

Fig. 7 and 8 show, respectively, the recordings and the PSDs of ambient vibration tests on the roof and at the floor of sector 4 (see Fig. 6).

The energy content of the daytime signal is significantly different from the nightly one at frequencies below 10 Hz. Moreover, at least three natural frequencies may be identified: at about 2-3 Hz, at about 6-7 Hz and at about 9-10 Hz. Nightly measurements allowed to define the predominant frequency of amplification equal to 10 Hz and showed that the contribution of the higher modes could be misleading if only one set of data is acquired and no daily variations are taken into account.

Between 1 and 4 Hz, measurements showed the same level of amplification in hypogea and on surface during night. The same happened during the day, even if the level of energy is 10 times the nightly one. This confirmed that the dynamic behavior of the underground structures is complex: anthropogenic sources enhance differently the

frequencies of the dynamic system and may produce interaction with the structures at high frequencies, while the soil-structure interaction should be searched at low frequencies.
Fig. 9 highlights again the complex dynamic behavior of the underground structures.

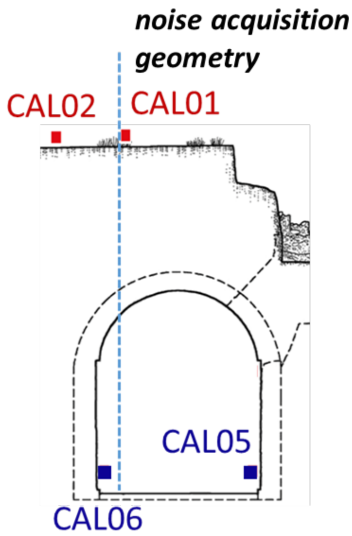

Fig.6. (a) Perspective drawing of one vertical of investigation with indication of the position of instruments CAL01, CAL02, CAL05 and CAL06.

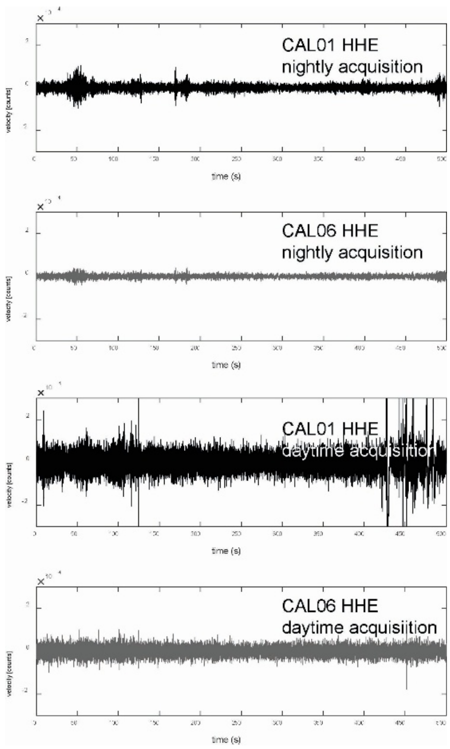

Fig.7 Recordings obtained at the stations CAL01 and CAL06 during nightly acquisition (upper panel) and daytime acquisition (bottom panel)

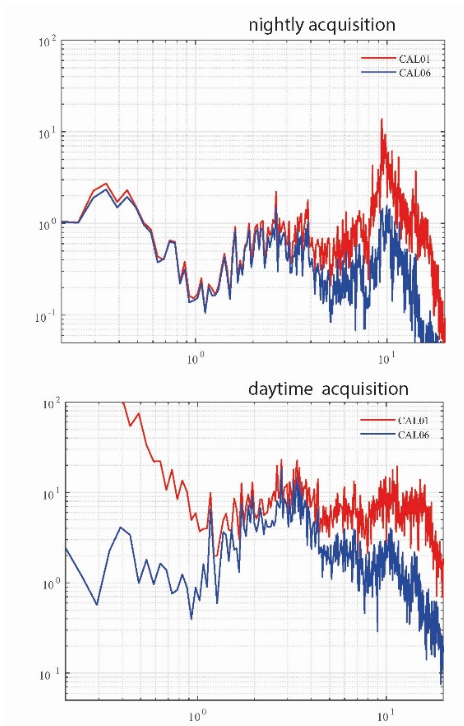

Fig.8. Power spectral densities of ambient vibration tests (PSD) of the recordings in Fig.7. E-W component.

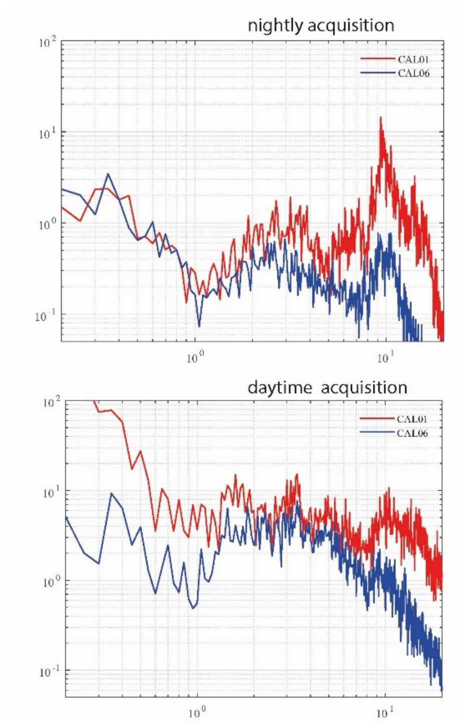

Fig.9. Power spectral densities of ambient vibration tests (PSD) of the recordings in Fig.7. N-S component.

V. CONCLUSIONS

Our results indicate that the dynamic characteristics of the structure (i.e. the elasticity modulus) seem not homogeneous along the investigated sides.

Environmental vibrations from anthropogenic sources, including construction activities, vehicular and rail traffic can interfere with the surrounding built environment. Often these sources can contribute to increasing the overall vulnerability of structures, especially in the case of valuable structures that are already damaged or characterized by deteriorated elements.

At the same time, the modes identification may benefit of the anthropogenic sources which enhance differently the frequencies of the dynamic system.

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