VIBRATION ANALYSIS OF THE LATERAN OBELISK

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ABSTRACT :

The purpose of the paper is to study the vibrational characteristics of the Lateran Obelisk in Rome as part of general study being performed for preservation purposes. The study analyses the data obtained by a temporary seismometer array, deployed in different configurations. Data processing was performed in both time and frequency domain. The analysis pointed out the first resonance frequencies and the corresponding modal shapes of the Obelisk. A finite element model was developed and a comparison was made between analytical and experimental modal shapes. The spectral analysis of ambient noise records obtained near the Obelisk does not show local amplification of ground motion due to soil effects. The dynamic response of the site is influenced by the presence of buried constructions.

KEYWORDS: ambient vibration, experimental analysis, seismic input, dynamic behaviour

1 INTRODUCTION

Monuments are the witnesses of history. Monuments are also the witnesses of the historical environmental phenomenon, whose knowledge requires several centuries of observations. This is certainly true for the earthquakes, for which the return periods used in the structural design are very long. As a matter of fact the history of Italian seismicity has been reconstructed also thanks to the historical documents, which reported descriptions about the damages of several world-famous monuments that have suffered to various degrees during past earthquakes (Bongiovanni et al., 1990). The analysis and interpretation of the historical documents about any structure should also accounting for all the changes occurred on it. It is worth pointing out that this information is almost well documented for monuments, but not for other buildings.

Besides, it is highly probable that factors other than earthquakes caused deterioration of historical monuments. For example, in the last century traffic-induced vibrations, which did not exist at the time of construction of all the historical monuments, certainly played an important role (Clemente 1995, Clemente et al. 1994, Clemente & Bongiovanni 1993). An important role played also the presence of other buildings around them.

One of the well-known historical monuments, for which all these features are present, is the Lateran Obelisk near Piazza San Giovanni in downtown Rome (Fig. 1). The purpose of this paper is to study the vibrational characteristics of the Obelisk and to asses possible effects of the earthquakes on it. A finite element model has been set up on the basis of the experimental results, and has been used for the seismic analysis of the structure.

2 AMBIENT VIBRATION IN THE OBELISK

The Egyptian Lateran Obelisk was built in the 15th century B.C. by Thutmosis III and Thutmosis IV and put in the Karnak Temple. The first Roman Emperor Octavianus Augustus (27 B.C. – 14 A.D.), when he first conquered Egypt, planned to take the Obelisk to Rome, but he had to give up his plan because of the size of the structure. It was Constantine I (306-337 A.D.) that ordered to remove and raise it at Constantinople, the new capital of the Roman Empire, but he died when the Obelisk was still in Egypt at Alexandria. Finally his son Constantius II (337-361 A.D.) took the Obelisk to Rome and fixed it at the central reservation, the so called “spina”, of the Circus Maximus in 357, next to the Flaminio Obelisk. After the decline of the Roman Empire the area of Circus Maximus was abandoned. The Obelisk fell down due to unknown reasons and broke into

three parts. The interest in Egyptian culture grew up again in 16th century, and Pope Sixtus V ordered the search for the Obelisk. It was found in 1587 and on August 3rd, 1588, raised in San Giovanni in Laterano, strategically one of the most important areas in Rome, according to the project of the architect Domenico Fontana. It is the tallest obelisk in Rome and the largest standing ancient Egyptian obelisk in the world, weighing over 2300 *kN*.
The Obelisk is 32.18 *m* tall and rests on a rectangular prismatic pedestal, about 10 *m* tall (the original pedestal was destroyed during the removal work from the Karnak Temple), which in turn is positioned on a wide stone base, whose depth is not known as well as the foundation conditions. A Christian cross is at its apex, the total height being 45.70 *m*. The Obelisk itself is made of three monolithic tapered red granite blocks. The three blocks exhibit various cracks, which are visible particularly near the contact surfaces between the blocks. Externally visible metallic links and small pieces of granite added during past restorations connect the blocks to each other.
It is worth pointing out that the Obelisk did not suffer any significant effects due to Avezzano Earthquake of January 13th, 1915, which caused the collapse of a statue on the façade of the Basilica of San Giovanni in Laterano.

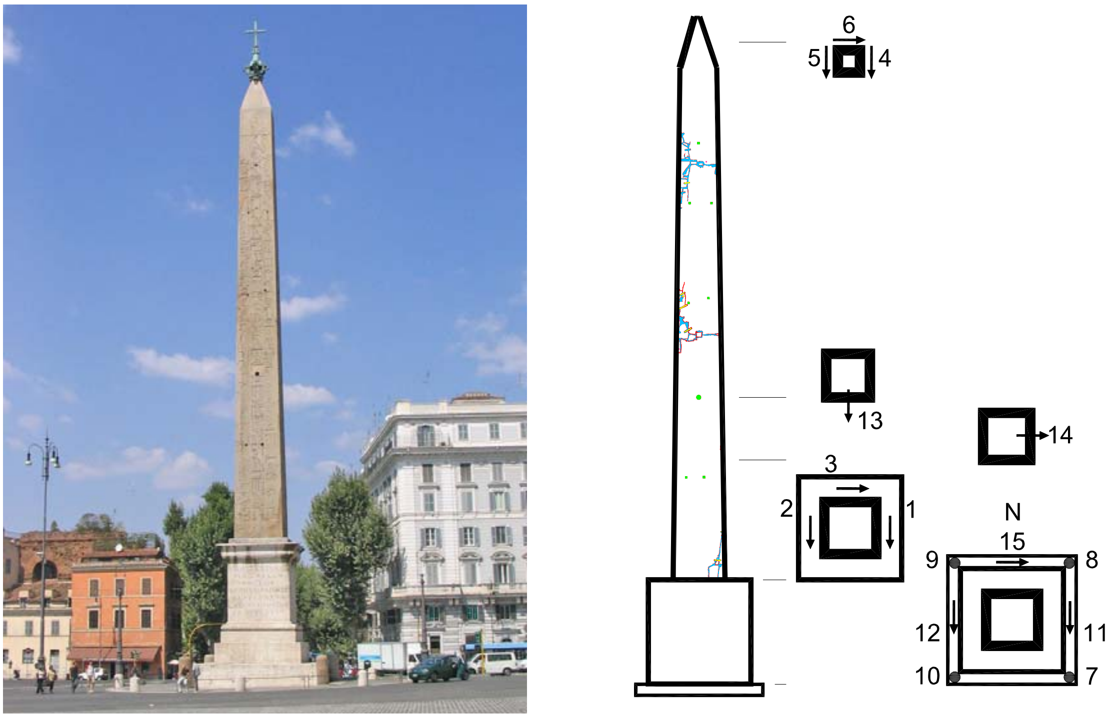


Figure 1 The Lateran Obelisk and seismometer locations

2.1 *Configurations and tests*

The experimental analysis has been carried out by a temporary seismometer array composed of 15 SS-1 uniaxial velocity sensors (natural frequency 1.0 *Hz*) and 2 K-2 digital recorders (Fig. 2). Several measurements have been carried out. Traffic induced vibrations of various intensities have been recorded during the day but also ambient noise during the night. Anyway, vibrations due to the power generator were always present, but they had no influence on the dynamic response of the Obelisk because of their frequency content. In spite of that, in order to eliminate the noise due to the power generator, the acquisition systems have been powered by means of a battery during a time interval of one test. The choice of the sensor locations has been influenced by their accessibility and the presence of a plane surface (Buffarini et al., 2007).

2.2 *Data analysis*

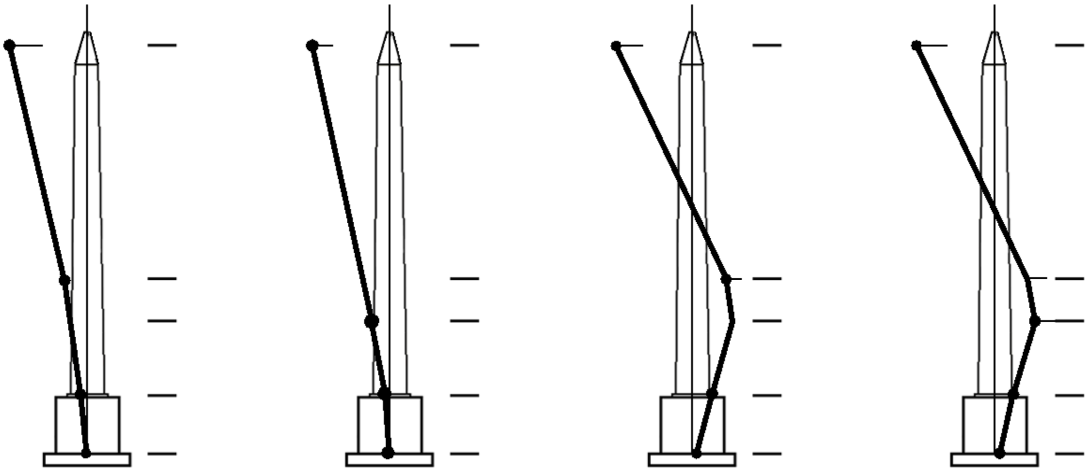
For all the recordings, obtained with a sampling rate of 200 *p/s*, both time and frequency domain analysis have been performed, by plotting the peak and effective values of the velocity of all the time-histories and the power spectral density (PSD) functions; the cross spectral density (CSD) function, with the corresponding phase factor and coherence function, was moreover computed for selected couples of records.

In Tab. 1 peak and effective values of the velocity are reported for the different locations of the seismometers. The effective values have been calculated over successive time intervals lasting 1.28 *s*. Peak values of the velocity are low on the basement while become important at the top.
Spectral analysis showed a first mode corresponding to the peak at 1.27 *Hz* in the NS direction and a second mode, almost at the same frequency, in the WE direction. The third and the fourth modes, in the NS and WE direction are associated to frequencies of 6.15 *Hz* and 6.73 *Hz*, respectively. Modal shapes are plotted in Fig. 3, while the numerical value of the normalized modal shapes are in Tab. 2.

Figure 2 – Sensors on the basement and at the top of the Obelisk

Table 1 Peak and effective values of velocity

Sensor/Direction	*Peak Velocity (mm/s)*	*Effective Velocity (mm/s)*
Basement – NS	0.0991	0.0359
Basement – UP	0.1424	0.0427
Basement WE	0.1244	0.0508
Pedestal – NS	0.1714	0.0714
Pedestal – WE	0.1275	0.0418
Intermediate – NS	0.2194	0.0954
Intermediate – WE	0.1492	0.0654
Top – NS	0.7055	0.2477
Top – WE	0.4973	0.1569



Mode 1 – NS
f = 1.27 Hz

Mode 2 – WE
f = 1.27 Hz

Mode 3 – NS
f = 6.15 Hz

Mode 4 – WE
f = 6.73 Hz

Figure 3 Experimental modal shapes

Table 2 Normalized experimental modal shapes

Sensors	*Mode 1 – NS* *f = 1.27 Hz*	*Mode 2 – WE* *f = 6.15 Hz*	*Mode 3 – NS* *f = 1.27 Hz*	*Mode 4 – WE* *f = 6.73 Hz*
Basement	0.02	0.02	-0.07	-0.08
Pedestal	0.09	0.08	-0.25	-0.22
Intermediate	0.30	0.24	-0.41	-0.50
Top	1.00	1.00	1.00	1.00

3 VIBRATION ANALYSIS AT THE SITE

Two free-field velocimetric surveys were carried out close to the Obelisk, in order to analyse the local seismic response and to characterise possible ground motion amplification effects.

During the velocimetric survey on the structure, records of ambient noise were obtained in 2 temporary stations respectively located about 10 *m* S (S1=St1) and 30 *m* SW (S2=St2) of the Obelisk (Fig. 4). Each station was instrumented with 3 velocimeters SS1, triaxially arranged. The horizontal sensors were oriented N160 and N70, according to the Obelisk sides and the sensors located on the structure; these directions will be indicated as NS and WE in the following. Three records of 15 *min* were acquired in each station with a 200 *p/s* sampling rate; the acquisition was performed early in the morning with the aim of reducing the disturbance due to street traffic.

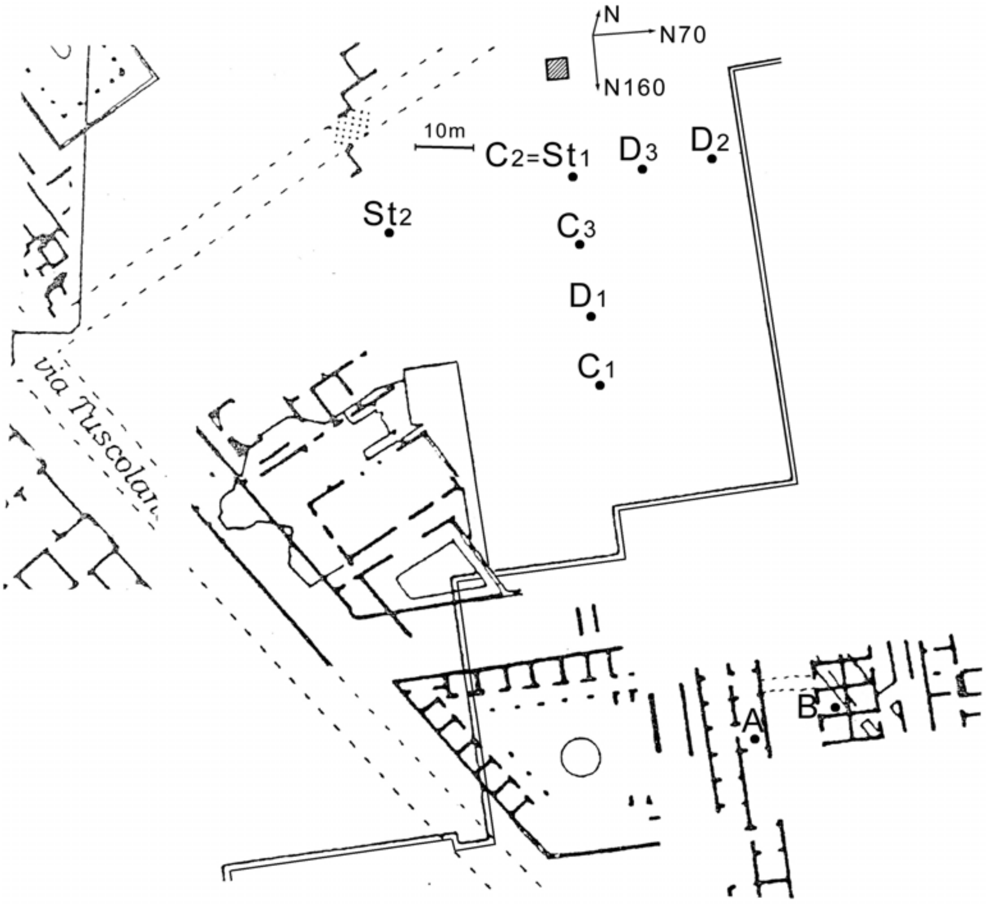


Figure 4 Sensor location on the soil

The recorded time histories have been analysed in the frequency domain, computing the Fast Fourier Transform in a 40 *s* moving window. Mean spectra (Fig. 6) as well as Horizontal to Vertical Spectral Ratios (HVSR – Nakamura, 1989) have been obtained for each station; since no relevant difference has been observed between NS/UP and WE/UP ratios, mean HVSRs are reported in Fig. 5.

No significant amplification effect has been pointed out by the HVSR, on the other hand a peculiar behaviour can be observed at frequencies > 8 Hz, where the spectral amplitudes of the vertical components of motion are remarkably higher than those of the horizontal ones. This effect could be related to caves and/or ancient structures that are known to be below the ground level.

In order to better analyse the site response, another velocimetric survey was performed. Ambient noise records were obtained with the same methodology along a superficial array (stations C1, C2, C3, D1, D2, D3 in Fig. 4) as well as in 2 stations (A, B in Fig. 4) located underground, on the basement of the S. Giovanni Church. Stations A and B operated in STA/LTA acquisition mode for about 24 hours and obtained numerous records until the memory card was full. The acquisition was triggered mainly overnight, when the level of the external noise was very low but no seismic event was recorded.

Figs. 7 and 8 show the mean spectral amplitudes and the HVSR at stations A and B, respectively. The amplitudes related to the vertical components are generally higher than the horizontal ones, however the difference is not so relevant as that previously observed from surface measurements. The HVSRs do not point out site amplification effects, since the peak at about 1 *Hz* cannot be taken as significant due to its low level.

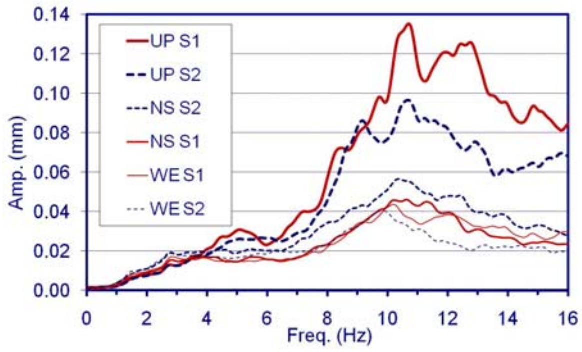


Figure 5 Fourier spectra at S1 and S2

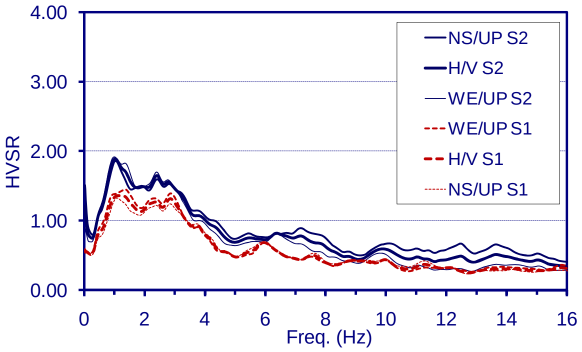


Figure 6 Spectral ratios at S1 and S2

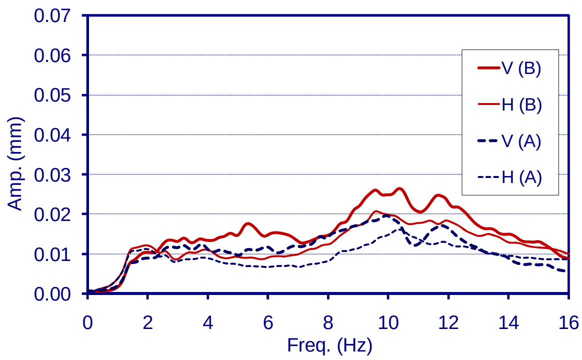


Figure 7 Spectral amplitudes at A and B

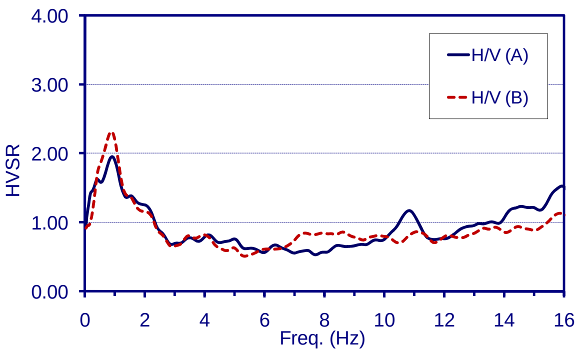


Figure 8 Spectral ratios at A and B

Fig. 9 shows the mean spectra of the surface records (station S1 of the first survey coincides with station C2 of the second one): the amplitudes of the vertical components are remarkably higher than the horizontal ones for all the stations, as already observed from the results of the first survey. It is also worth pointing out that the values of the spectral amplitudes result to be related to the traffic noise level rather than the location of the measurement, the lower ones being observed in the nocturnal records.

In order to check whether the response observed nearby the Obelisk affects the structure, some records obtained on the basement of the Obelisk have been analysed according to the same methodology used for the records at the site. No significant difference among sensor location or recording time has been observed, therefore the mean spectral values obtained from all the samples and the considered sensors have been considered: no significant difference results between the spectral amplitudes of the horizontal and vertical components of motion at the basement of the Obelisk (Fig. 10).

In short, the analysis of ambient noise recorded at both ground level and underground has not pointed out amplification effects near by the Obelisk. This result is in agreement with the geological condition of the site which was reconstructed through the available down-hole data and does not show a significant impedance contrast between the superficial volcanic deposits and the lower ones.

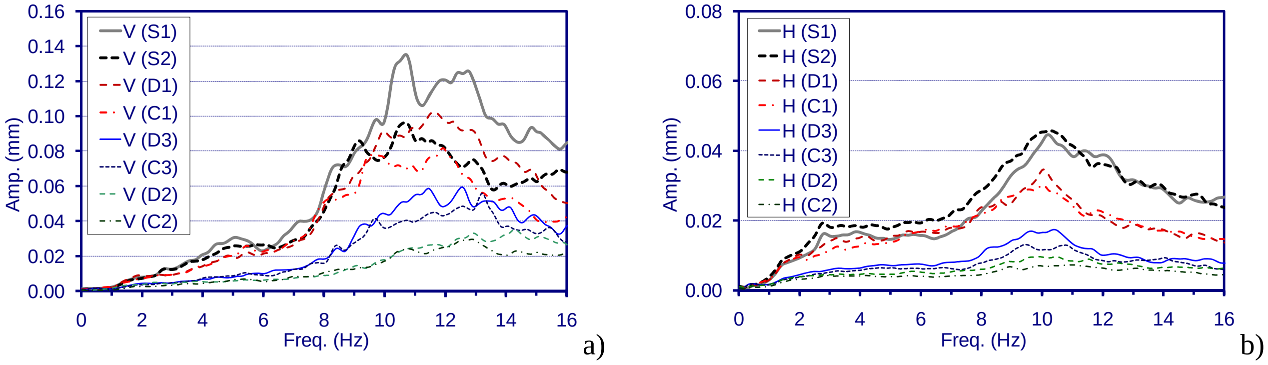


Figure 9 Spectral amplitudes on the soil – a) vertical, b) horizontal

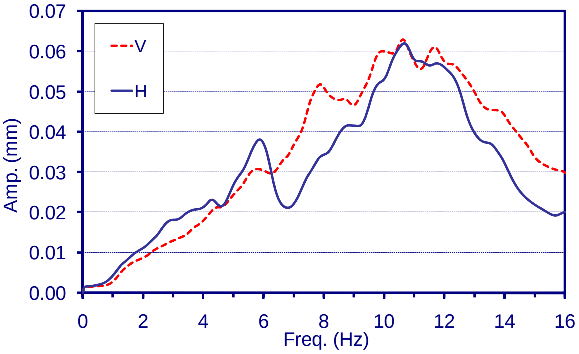


Figure 10 Mean spectral amplitudes on the basement

4 NUMERICAL MODEL

The numerical model has been set up by using solid elements. The Obelisk has been divided into four parts in which the material properties are constant. These have been individualized by means of the sensor locations. In more details, the weight per unit volume have been fixed for each part according to the well known values in literature, the Young’s modules have been changed in order the numerical first frequency and modal shape to reproduce the experimental ones (see table 2). This has been done by using an automatic procedure set up on purpose. In table 3 the material characteristics are shown.

It is worth pointing out that, the geometry of the foundation being unknown, also the height of the basement has been changed in order to reproduce the horizontal displacement on the basement. The mass of the soil-basement system has not been considered.

The modal analysis gave the first two modal shapes in the NS shown in Fig. 11.

The model has been used for the non-linear static analysis. Between the basement and the pedestal, and so between the pedestal and the Obelisk, no tensile resistant gap elements have been introduced. The structure has been subjected to a its self-weight and to an increasing horizontal load distribution that reproduces the effects of the first modal shape. In Fig. 12 the diagram of the acceleration versus the displacement at the top of the

Obelisk is plotted. The loss of stability is apparent for very low values of acceleration, the large displacement being mainly related to the relative rotation between the Obelisk and the pedestal.

Table 3 Material characteristics

Part	*Weight per unit volume (kN/m^3)*	*Young's modulus (N/mm^2)*
Soil - Basement	-	24550
Pedestal	22.00	23100
Low Obelisk (to sensor 13)	27.00	25800
High Obelisk	27.00	25800

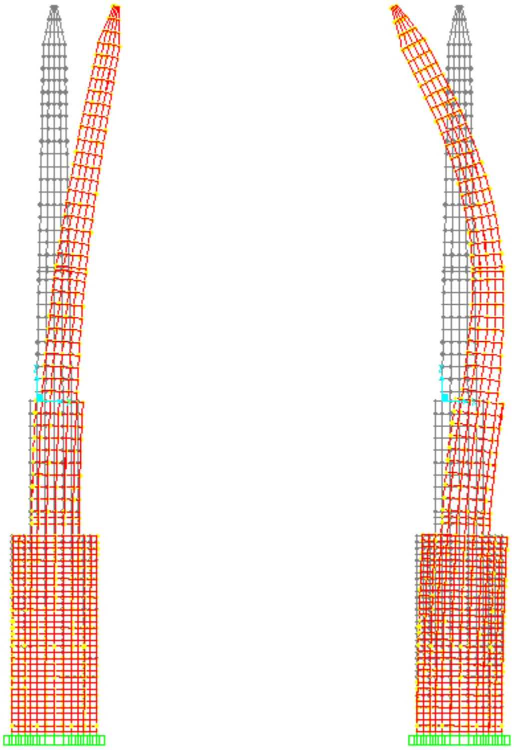


Figure 11 FEM: modal shapes in NS direction

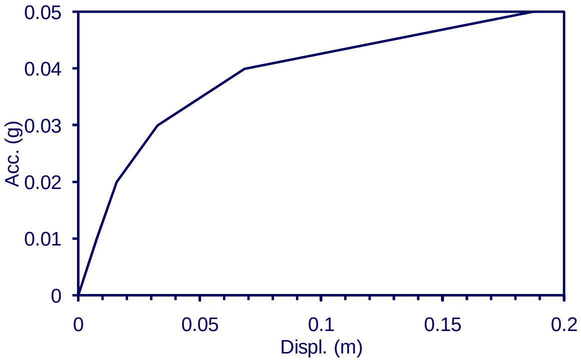


Figure 12 Acceleration–displacement diagram

5 CONCLUSIONS

In the framework of a general study performed for preservation purposes, the vibrational characteristics of the Lateran Obelisk in Rome and the local site response have been analyzed. The study has been carried out by means of a temporary seismometer array, deployed in different configurations. The obtained data have been processed in both time and frequency domain. On the basis of the recorded date a finite element model has been performed and used for a static analysis of the Obelisk under seismic loads. The main results can be summarized as follows:

- the first four frequencies and the corresponding modal shapes have been pointed out;
- under vibrations of low amplitudes, such as ambient and traffic-induced vibrations, the Obelisk and its pedestal behave as a whole;
- no soil amplification of horizontal components has been found;
- significant amplifications of the vertical component are present at frequencies higher than 10 *Hz*, probably due to adjacent and/or buried structures; these amplifications are not apparent on the basement and therefore do not influence the input to the Obelisk;
- the seismic analysis, performed by means of non linear static analysis, has confirmed the high vulnerability of such structures to seismic actions.

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