In Situ Traffic Vibration Monitoring and Non-Destructive Analyses of the Egyptian Obelisk of San Giovanni in Laterano in Rome

The Egyptian Obelisk of Piazza S. Giovanni in Laterano in Rome, Italy, was previously located at the Circo Maximo by emperor Costanzo the IInd; it was positioned at the current location in the XVI century by the architect Domenico Fontana. The obelisk stands on a 10m tall basement and, considering also the crux on the top, the total height of the monument is 45 meters. An extensive campaign of six months ambient vibration monitoring, sonic tomography and radar investigation has been carried out by ENEA for the structural evaluation of the obelisk

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Introduction

The "Obelisco lateranense" is 32 m tall, and is composed by three blocks of granite connected to each other and at the base by three joints, the mechanical characteristics of which have been investigated and described in this article. The obelisk stands on a basement 10m tall and, considering also the crux on the top, the total high of the monument is 45 meters. Regarding its general structural conditions, once again it is possible to verify the high level of the Renaissance architectural skill while the three blocks are perfectly connected. The Non-Destructive Analyses have highlighted the ingenious system of "crux joints" realized by the architect Gian Domenico Fontana to recompose the three blocks and the complex and useful dislocation of the blocks of granite at the base of the obelisk. The following in situ experimental campaign has been carried on for the structural evaluation of the obelisk:

- Structural monitoring and dynamic characterization by ambient vibrations;
- Non-Destructive Analyses for the mechanical characterization of materials and identification of the metallic bars in the granite.

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Structural Monitoring and Dynamic Characterization

The traffic close to the obelisk is regulated by 4 traffic lights, at each green light there is at least one heavy truck or bus. The traffic-light in via dell'Amba Aradam has a red light time of 40 sec and green light time of 80 sec. Therefore, to achieve the traffic lights vibrations, the time history data are 120 sec long. Figure 1 shows the frequency contribution to the RMS acceleration at different levels of the obelisk recorded on December 1st, 2007, at time 16:37:53. In the graph, the signatures at 1.3 Hz and 6.1 Hz are evident, corresponding to the principal components of the Obelisk in the elastic phase. The figure also shows the time history and spectrogram of the induced acceleration when traffic light is green.

In terms of energy, traffic solicitations can be normalised with respect to a reference spectral acceleration, and evaluated comparing the spectral contents of the reference and the measured accelerations. In other words, a correspondence between the traffic effect and the reference earthquake of the site has been defined This way it is possible to evaluate the effects of the traffic vibrations in terms of normalised accelerations with respect to the reference earthquake. The curve MAX <Sa(T)_Traffic> is the envelope of the spectra at the base of the obelisk at 1.3 Hz and 6.1 Hz (the principal modes of the obelisk). The ratio between traffic spectrum and site spectrum at the principal frequencies of the obelisk are shown in Table 1.

The equivalent seismic action due to the traffic is 0.6% of the seismic demand for the Ultimate Limit State (Ref. OPCM 3431) and 0.04% of the site macro seismic spectrum.

With reference to the UNI9916 of 2004, the maximum ambient vibrations allowed for class 3 structures (monuments) is 0.25 cm/sec. Table 2 represents the ratio between these maximum values and the traffic equivalent velocity spectrum at the natural frequencies of the obelisk.

Sonic and Radar NDT Investigation

The Obelisk is assembled by three blocks of granite jointed by hinges with unknown mechanical characteristics. Up to 4 zones have been identified to characterize the geometrical and mechanical behaviours of the obelisk, therefore both sonic and

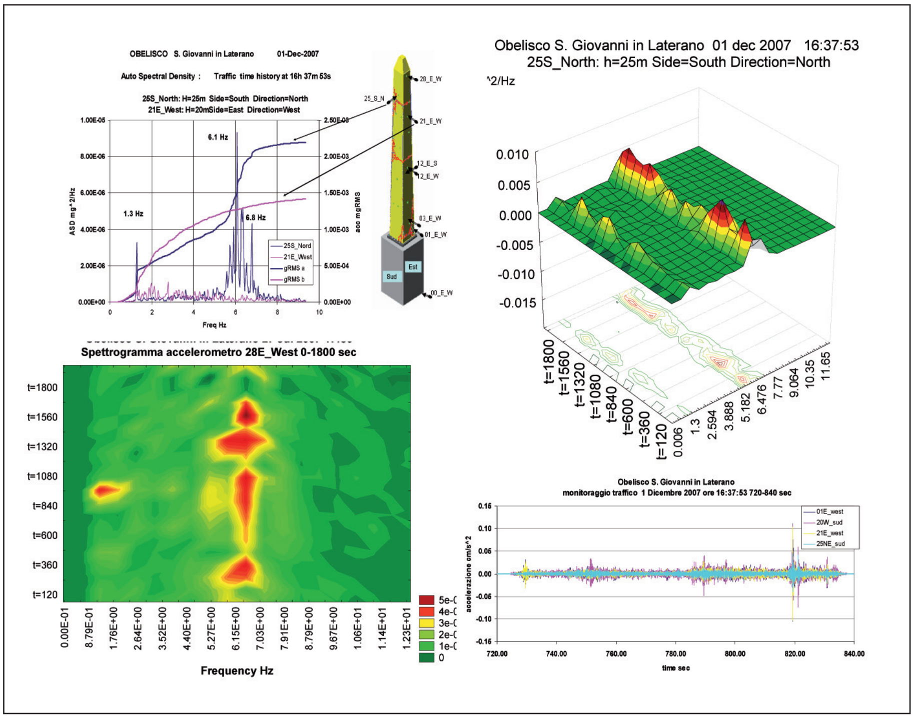

FIGURE 1 Power Spectral density and Frequency contribution to the RMS acceleration value (in cm/sec^2). Spectrograms and time history during the green phase of the traffic light
Source: ENEA

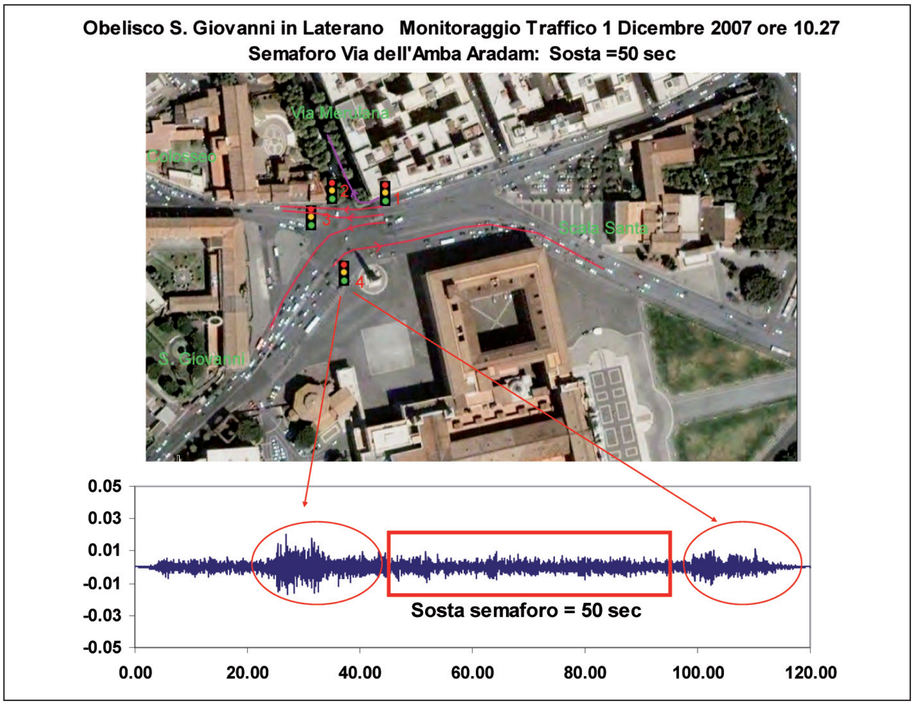

FIGURE 2 Accelerations due to the traffic from via dell'Amba Aradam to Piazza di porta S. Giovanni
Source: ENEA

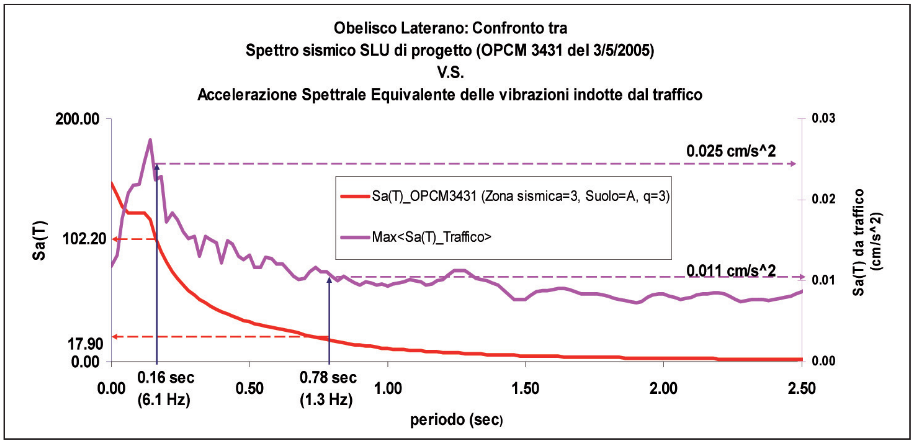

FIGURE 3 Confrontation between the maximum equivalent spectrum due to the traffic and the design earthquake spectrum of the site (OPCM 3431 the 2005-may-3th)
Source: ENEA

Mode No.	Hz	Sa(T)_traffic/ Sa(T)_site	Sa(T)_traffic/ Sa(T)_OPCM
1	1.3	0.013 %	0.600 %
2	6.1	0.040 %	0.024 %

TABLE 1 Ratio between traffic and site spectrum at the principal frequencies of the obelisk
Source: ENEA

Mode No.	Frequency Hz	Max<Sv(T)_Traffic>	Ratio Max<Sv(T)_Traffic>/ UNI9916
1	1.3	0.0034	1.36%
2	6.1	0.00057	0.22%

TABLE 2 Ratio between the maximum allowed ambient vibration and traffic equivalent velocity spectrum
Source: ENEA

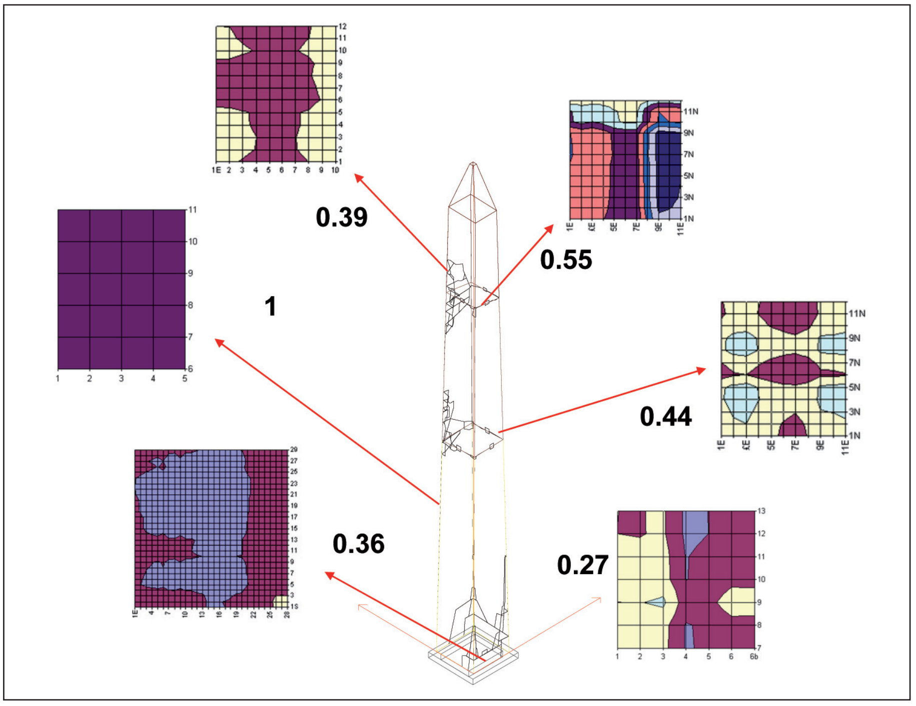

FIGURE 4 Sonic tomography at different levels of the obelisk
Source: ENEA

radar investigations have been performed to identify the geometry and characterize the mechanical properties. Knowing the differences between the mechanical characteristics of the representative zones of the obelisk it is possible to perform a parametric analysis of the dynamic response in terms of mechanical characteristics normalised with respect to the reference zone. Since the mechanical properties for the non-damaged zone are unknown, a parametric analysis have been performed and, for each parametric value, the properties for the other zones have been assessed according to the sonic and radar NDT experimental results. Figure 4 shows the sonic tomography results at different levels of the Obelisk. The sonic tomography allowed to verify the presence of iron staffs and bronze plates at the base of the Obelisk and also the presence of the joints with crux to avoid sliding between the three blocks.

The radar investigation of the Obelisk has been performed in order to evaluate the characteristics of the joints. The following results were achieved:

- The base of the Obelisk has non-homogeneous parallel blocks along the east, north and west sides.
- Inside each ring there are non-homogeneous materials.
- Metallic plates and rods in symmetric positions 50-50cm deep

Numerical Analysis

The numerical analysis of the Obelisk has been performed assuming the properties of the materials as resulting by the NDT investigations and referenced to the parametric properties of the granite in good conditions. A parametric evaluation has been performed assuming different values of the elasticity modulus within the value range of 12 GPa and 45 GPa:

$$\rho_{granito} = 2700\ Kg/m^3; \quad \nu = 0.14;$$
$$1.25\ E{+}10 < \mathbf{E\ [Pa]} < 4.5E{+}10$$

A static non linear analysis has been performed considering the following distribution of the seismic action:

- type-a seismic forces applied at the gravity center of the obelisk

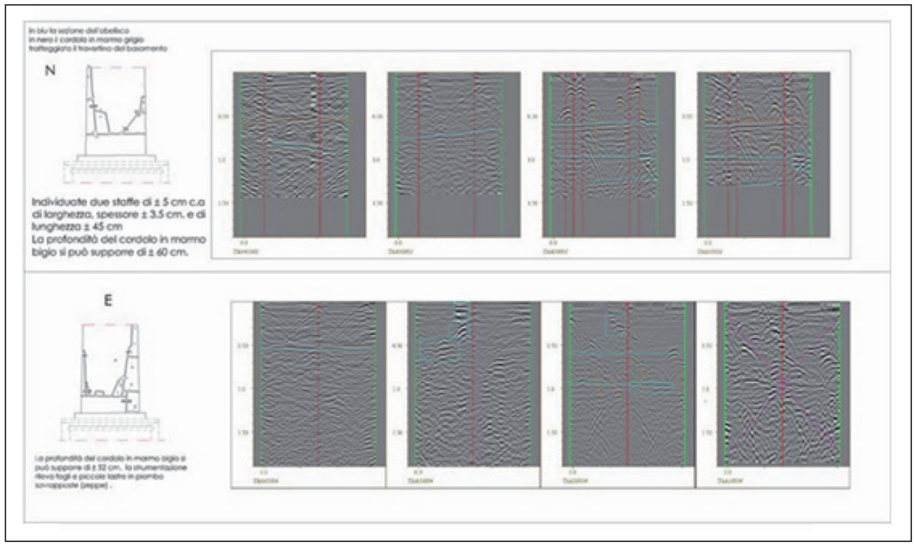

FIGURE 5 Radar echoes at the base of the Obelisk due to metallic bars and discontinuity between blocks
Source: ENEA

- type-b seismic forces distributed at the gravity centers of the blocks
- type-c seismic forces proportional to the first two modes

Table 3 summarizes the results of the numerical analysis with different seismic load distribution.

Conclusions

The identification of the dynamic response of the Egyptian Obelisk of Piazza San Giovanni in Laterano in Rome, Italy, has been performed by means of long-term monitoring of environmental loads due to traffic and/or microseisms. A series of non-destructive testing methods (sonic tomography and radar investigation) have been used to assess the material properties, the internal cracking and the hinges status. The numerical analysis of the obelisk has been performed knowing the differences between the mechanical characteristics of 4 representative zones by means of a parametric analysis with respect to the mechanical characteristics of the undamaged section.

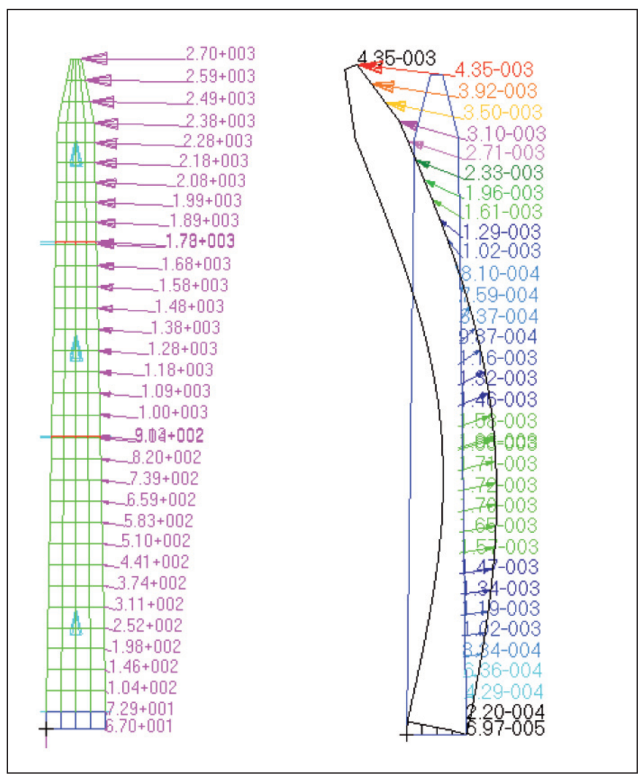

FIGURE 6 Distribution of seismic loads for type-C forces: a) Seismic load C_I, b) Seismic Load C_II
Source: ENEA

Seismic load:	Critical multiplier
a: Gravity + seismic action applied at the gravity center of the obelisk	11.25%
b: Gravity + seismic action distributed at the gravity centers of the blocks	12.0%
cI: Gravity + seismic action proportional to the first mode of the obelisk	12.5%
cI: Gravity + seismic action proportional to the second mode of the obelisk	15.0%

TABLE 3 Critical acceleration multiplier evaluated assuming different seismic load
Source: ENEA

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