STRUCTURAL EVALUATION OF THE EGYPTIAN OBELISK OF "SAN GIOVANNI IN LATERANO" IN ROME

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ABSTRACT

The "Obelisco Lateranense" is the tallest and most damaged Egyptian obelisk in Rome. It was positioned at the current location of Piazza San Giovanni in Laterano in the 16th century by Domenico Fontana connecting the three large fragments in which the obelisk was broken due to the crash from its previous location at the Circo Massimo. Therefore the structure of the obelisk must be assumed to be composed of three large heavy blocks of granite lying on each other, and at the base, by three hinges with unknown binding degree. The purpose of the experimental campaign has been to identify the dynamic response of the structure by means of long term monitoring of environmental loads due to traffic and/or microseisms. The expected structural damages of this obelisk due to settlement, vibrations or earthquake actions are sliding or rocking of the blocks when the horizontal inertial forces exceed certain limits, depending on the hinges binding degree. A series of non-destructive testing methods have been used to assess the material properties, the internal cracking and the hinges status. Endoscope visualization, 3D sonic tomography and radar analysis have applied for the mechanical and structural survey of the obelisk.

STRUCTURAL MONITORING AND DYNAMIC CHARACTERIZATION

The "Obelisco lateranense" is 32 m tall and it is composed by three blocks of granite connected each other and at the base by three joints whose mechanical characteristics have been investigated and showed in this article. The obelisk stands on a basement 10 m 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 architect Gian Domenico Fontana to recompose the three blocks, showing also their complex and useful repositioning at the base of the obelisk.
The experimental campaign has been carried in three phases:

A) Structural monitoring and dynamics characterization by ambient vibrations;

B) Non Destructive Analyses for mechanical characterization of the material and identification of the metallic bars in the granite.

Traffic monitoring

Within the period June-December 2007 up to 21 vibration data recording have been performed at different day time: early in the morning, heavy mid day traffic and low late night traffic.
The recorded data give an estimation of the environmental traffic vibration involving the obelisk.

The traffic close to the obelisk is regulated by 4 traffic lights and at each green light at least one heavy truck or bus runs. The traffic-light in via dell'Amba Aradam has a red light time of 40 sec duration and green light time of 80 sec.
Figure 1. shows the frequency contribution to the RMS acceleration at different levels of the obelisk recorded the 2007 December 1st at time 16:37:53. The signatures at 1.3 Hz and 6.1 Hz corresponding to the principal components of the Obelisk in the elastic phase are evident in the graph. The figure also shows the accelerometer positions and identification on the East and North sides of the obelisk (E.g. 28_E_W= level:28_Side:East_orientation: West)

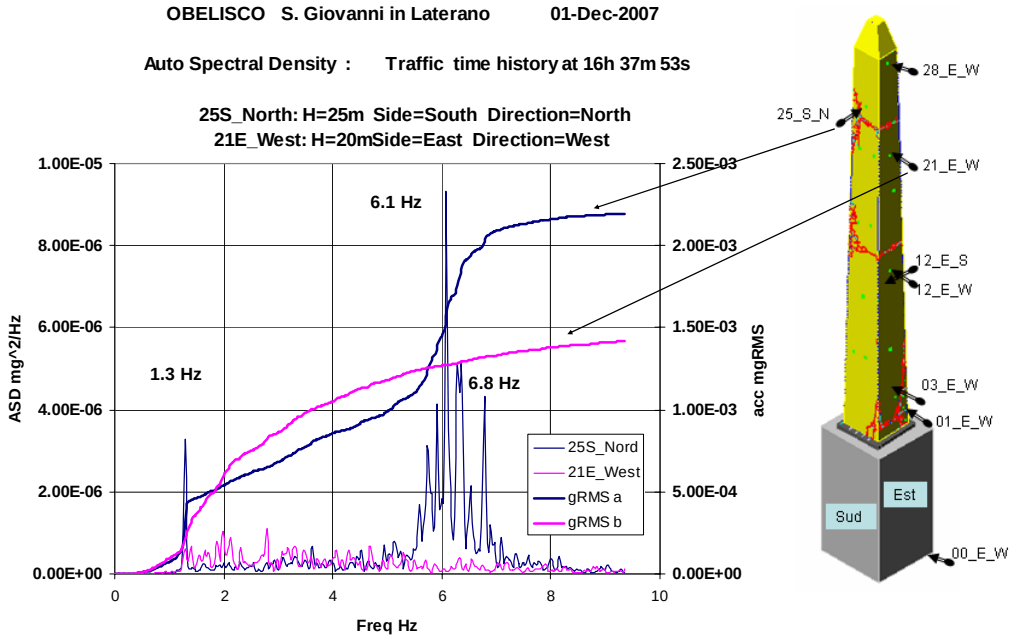
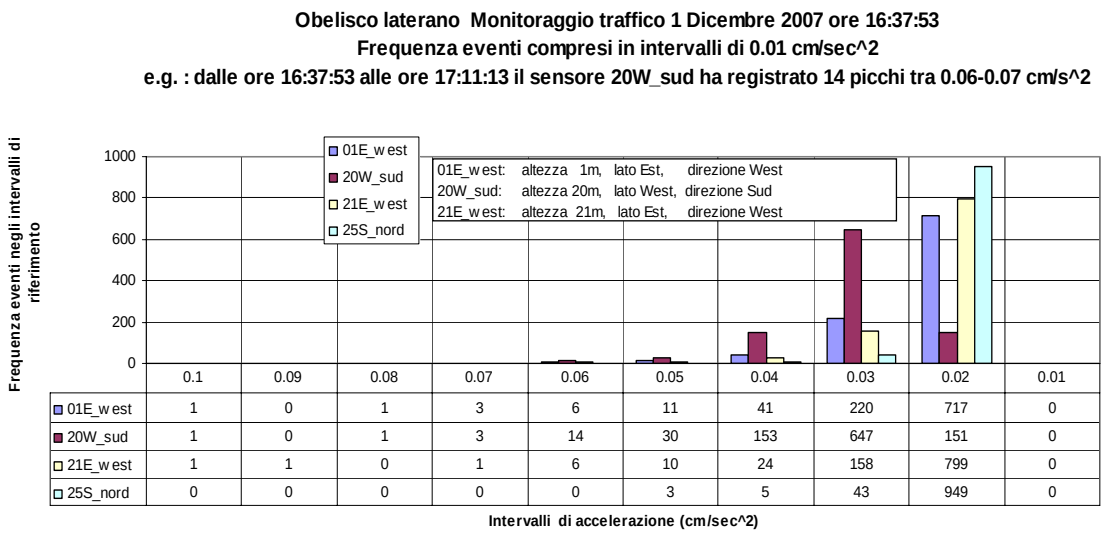


Figure 1 Power Spectral density and Frequency contribution to the RMS acceleration value (in cm/sec^2) of the accelerations 21E_west and 25S_North.

The principal mode frequencies and their contribution to the Root mean square accelerations are shown in figure 1. The RMS values (cm/sec^2) recorded by the two accelerometers near the top of the Obelisk are:

25_S_North = 0.0022 cm/sec**2 (RMS)
21_E_West =0.00142 cm/sec**2 (RMS)

The figure 2 shows the acceleration peaks at different levels of the Obelisk and the figure 3 summarizes the acceleration peaks recorded by the two accelerometers 01E_west, 20W_sud and 21E_west, 25S_North (i.e. the first is positioned at level 01 meter on the side East of the obelisk and oriented Westward, the latter is positioned at level 21 meters on the side West of the obelisk and oriented Northward)



	0.1	0.09	0.08	0.07	0.06	0.05	0.04	0.03	0.02	0.01
01E_west	1	0	1	3	6	11	41	220	717	0
20W_sud	1	0	1	3	14	30	153	647	151	0
21E_west	1	1	0	1	6	10	24	158	799	0
25S_nord	0	0	0	0	0	3	5	43	949	0

Figure 2 Distribution of acceleration peaks registered the 2007 December 1st at time 16:37:53 (e.g. The sensor 20W_Sud registered 14 acceleration peaks within the interval 0.05-0.07 cm/sec^2)

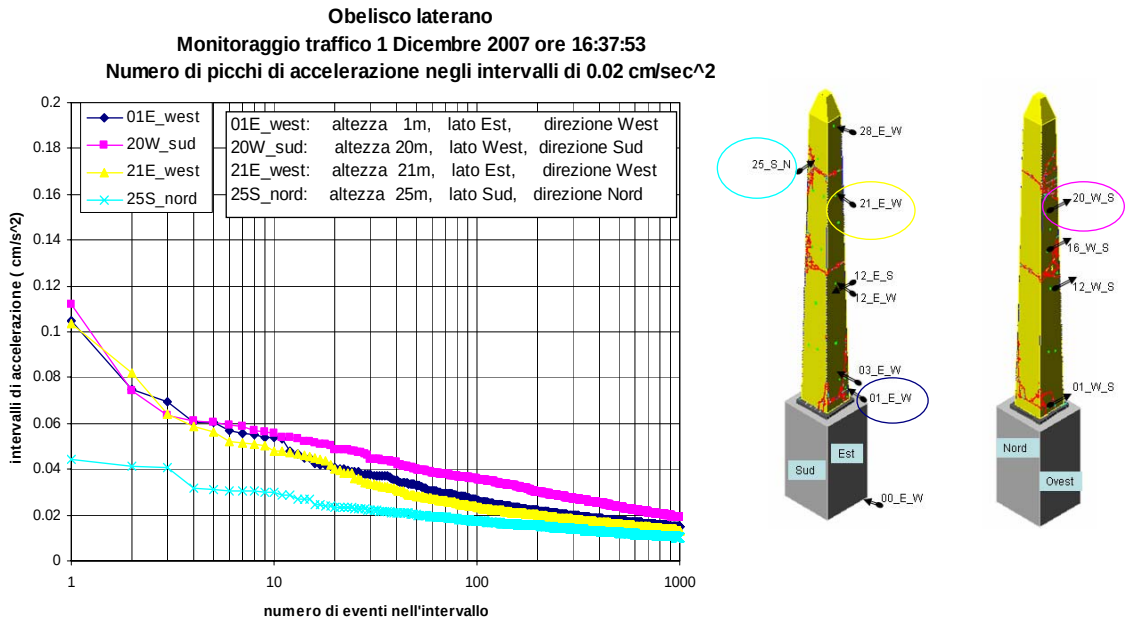


Figure 3 Number of acceleration peaks registered the 2007 December 1st at time 16:37:53 , duration 33^{m} 20^{s} (e.g. The sensors 01E_west, 20W_sud and 21E_West have registered one acceleration peak within the interval 0.1-0.12 cm/sec^2)

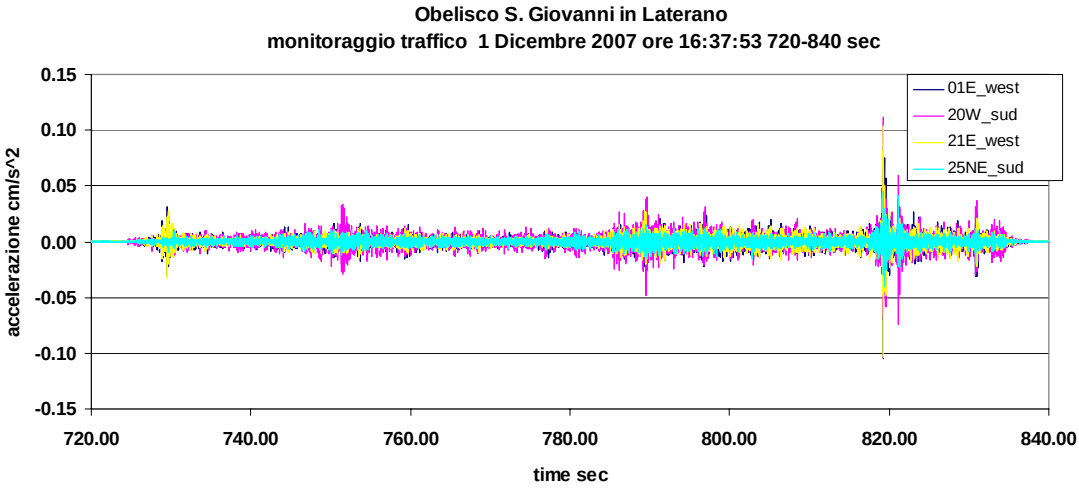


Figure 4 Time history recorded by the sensors 20E_Sud and 25S_Nord the 2007 December 1st during the time interval between 16:49:53 and 16:51:53 comprehensive of a complete traffic light sequence from via dell'Amba Aradam.

Traffic in the obelisk area is characterized by a dense flux of mainly light vehicles. The maximum traffic densities are in the late morning and afternoon. The figure 5 is a summary of accelerations due to traffic from via dell'Amba Aradam to Piazza di Porta San Giovanni.

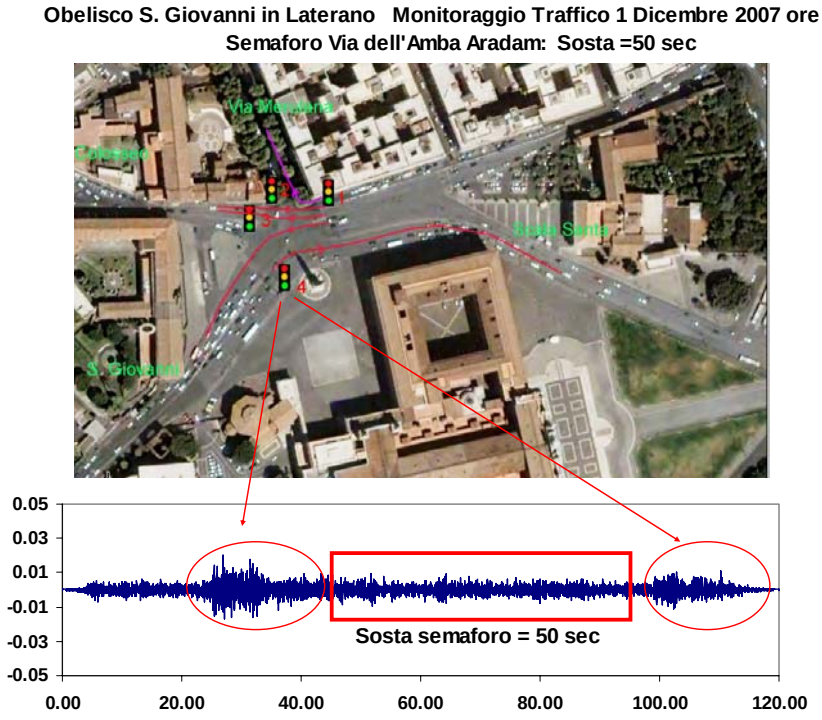


Figure 5 Accelerations due to the traffic from via dell'Amba Aradam to Piazza di porta S. Giovanni. effetto del transito veicolare da Via dell'Amba Aradam e Piazza di porta S. Giovanni

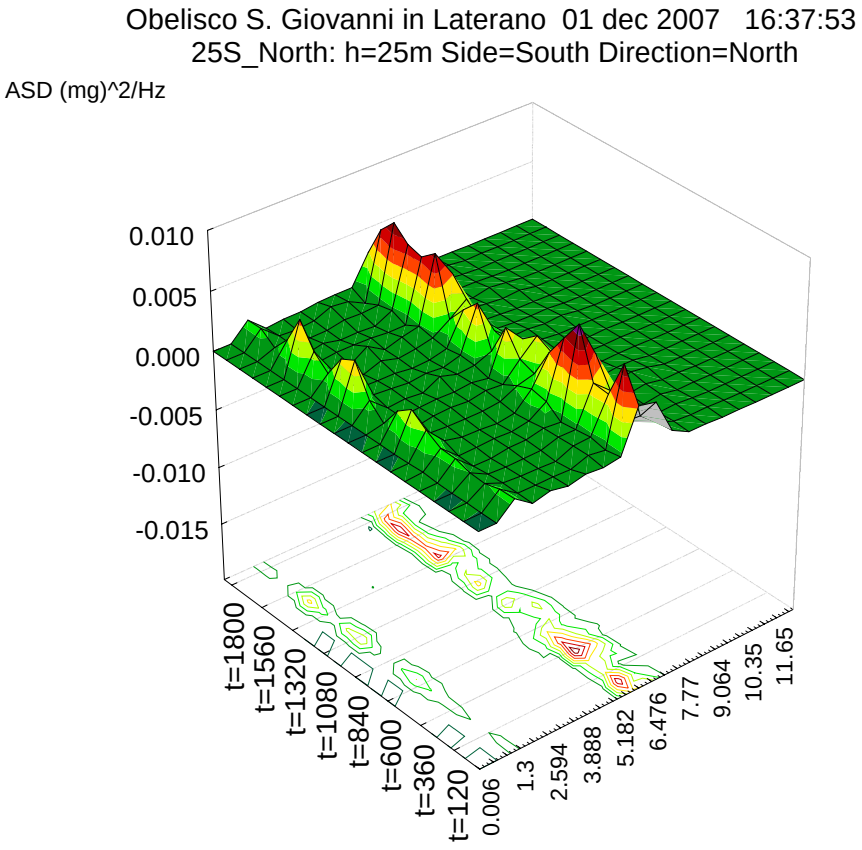


Figure 6: Power Spectral Density Spectrogram of accelerations recorded by 25S_Nord the 2007 Dicember 1st at time 16:37:53. The peaks at 1.3 Hz and 6.1 Hz together with the 60-80 seconds intervals due to the traffic light sequences are evident.

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, the correspondence between the traffic effect and the reference earthquake of the site has been defined.

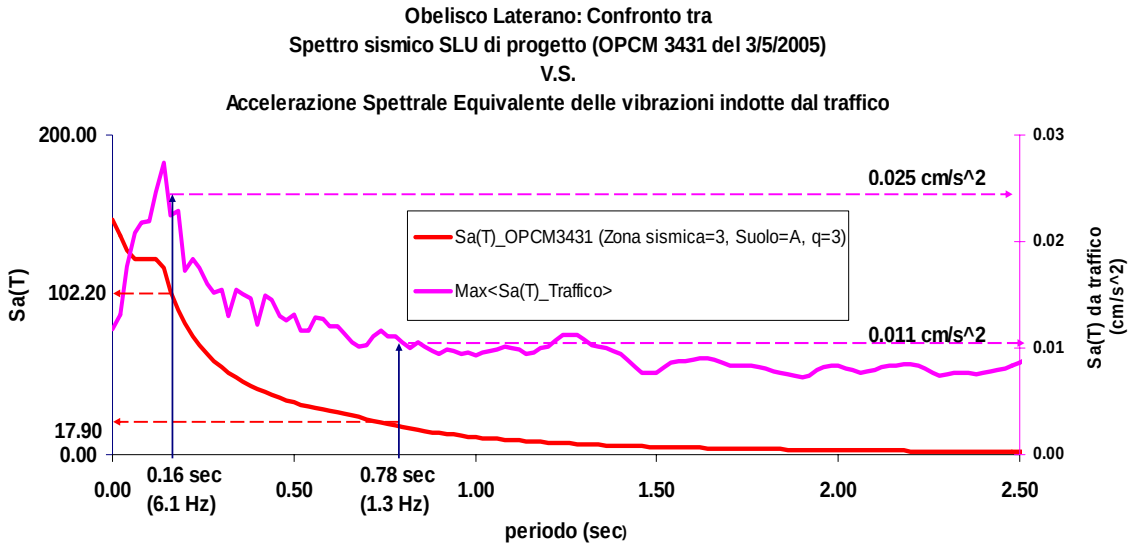


Figure 7: Comparison between the maximum equivalent spectrum due to the traffic and the design earthquake spectrum of the site (OPCM 3431 the 2005-may-3th)

In this way it is possible to evaluate effects of the traffic vibrations in terms of normalised accelerations 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 comparison between spectral accelerations are reported in table N°1

Table N°1

Mode N°	Freq. Hz	Period sec	Sa(T)_site cm/s^2	Sa(T)_OPCM cm/s^2	Sa(T)_traffic cm/s^2	Sa_traffic v.s. Sa_site	Sa_traffic v.s. Sa_OPCM
1	1.3	0.78	86.80	17.90	0.011	1.3E-4	6.1E-3
2	6.1	0.16	121.00	102.2	0.025	2.0E-4	2.4E-4

Accelerations have been normalised with respect to the energy spectral level (Housner Integral) of the reference spectra and the traffic vibration.
The ratio between traffic spectrum and site spectrum at main frequencies of the Obelisco are shown in table N°2

Table N°2

Mode N°	Freq. Hz	Ratio Sa(T)_traffic/ Sa(T)_situ	Ratio Sa(T)_traffic/ Sa(T)_OPCM
1	1.3	0.013 %	0.600 %
2	6.1	0.040 %	0.024 %

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

Table N°3

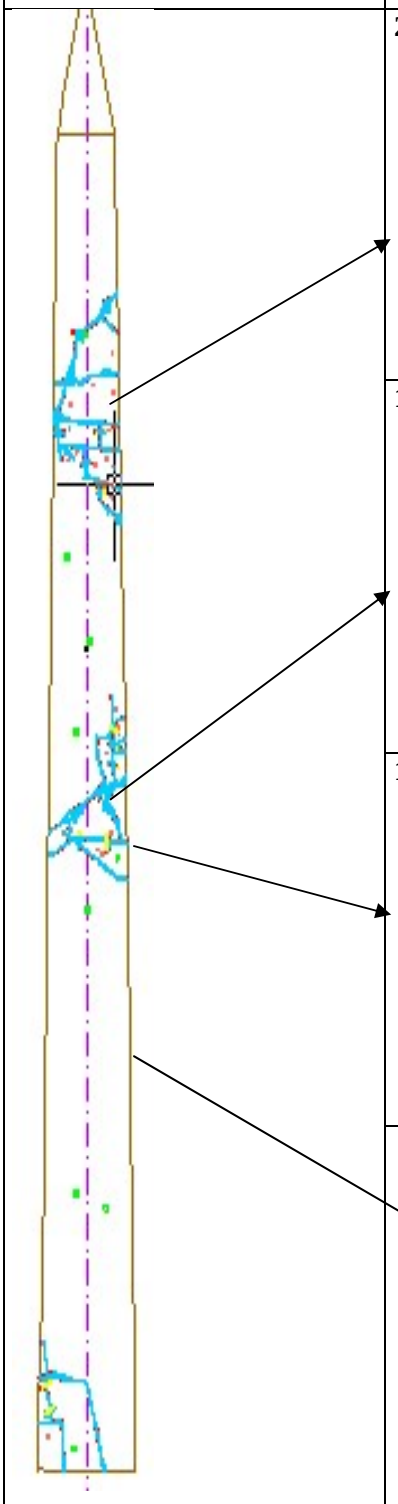
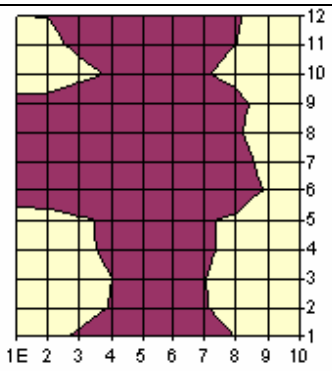
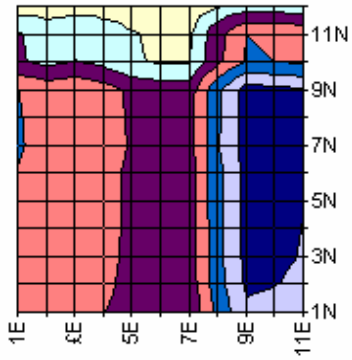
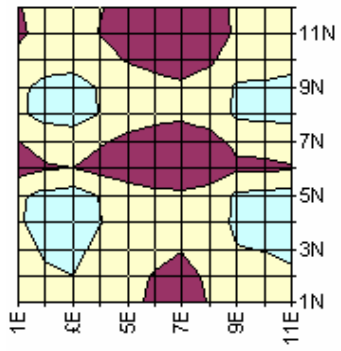
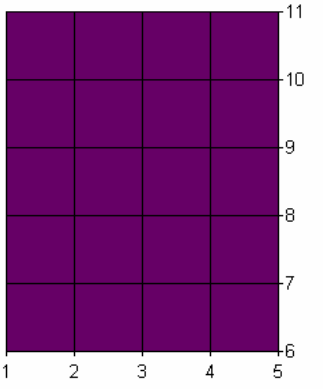
Mode N°	Freq. Hz	Max<Sv(T)_Traffic>	Ratio Max<Sv(T)_Traffic>/UNI9916
1	1.3	0.0034	1.36%
2	6.1	0.00057	0.22%

2. Structural identification by means of sonic tomography and radar investigations

The Obelisk is assembled by three blocks of granite jointed by hinges with unknown mechanical characteristics. Therefore the sonic and radar investigations have been performed for 4 type zones representative of the structural behaviour of the obelisk:

- Zone type 1: base
- Zone type 2: sections with fractures repaired by Domenico Fontana using granite blocks from ancient roman monuments
- Zone type 3: Joints between blocks
- Zone type 4: Granite in good conditions (no fractures)

Knowing the differences between mechanical characteristics of the 4 representative zones it is possible to make a parametric analysis of the dynamic response of the Obelisk with respect to the mechanical characteristics of the type 4 zone, assuming different values of mechanical properties of granite within minimum and maximum values in literature. For each parametric value of the mechanical properties for the type 4 zone, properties for the zone N° 1,2,3 have been modified according to sonic and radar NDT experimental results.

Position	Hight in meter	Section	1 no-defect granite <1 restored granite	Average index
	**20**			**0,39**
	12,40			**0,55**
	12			**0,44**
	10			**1**

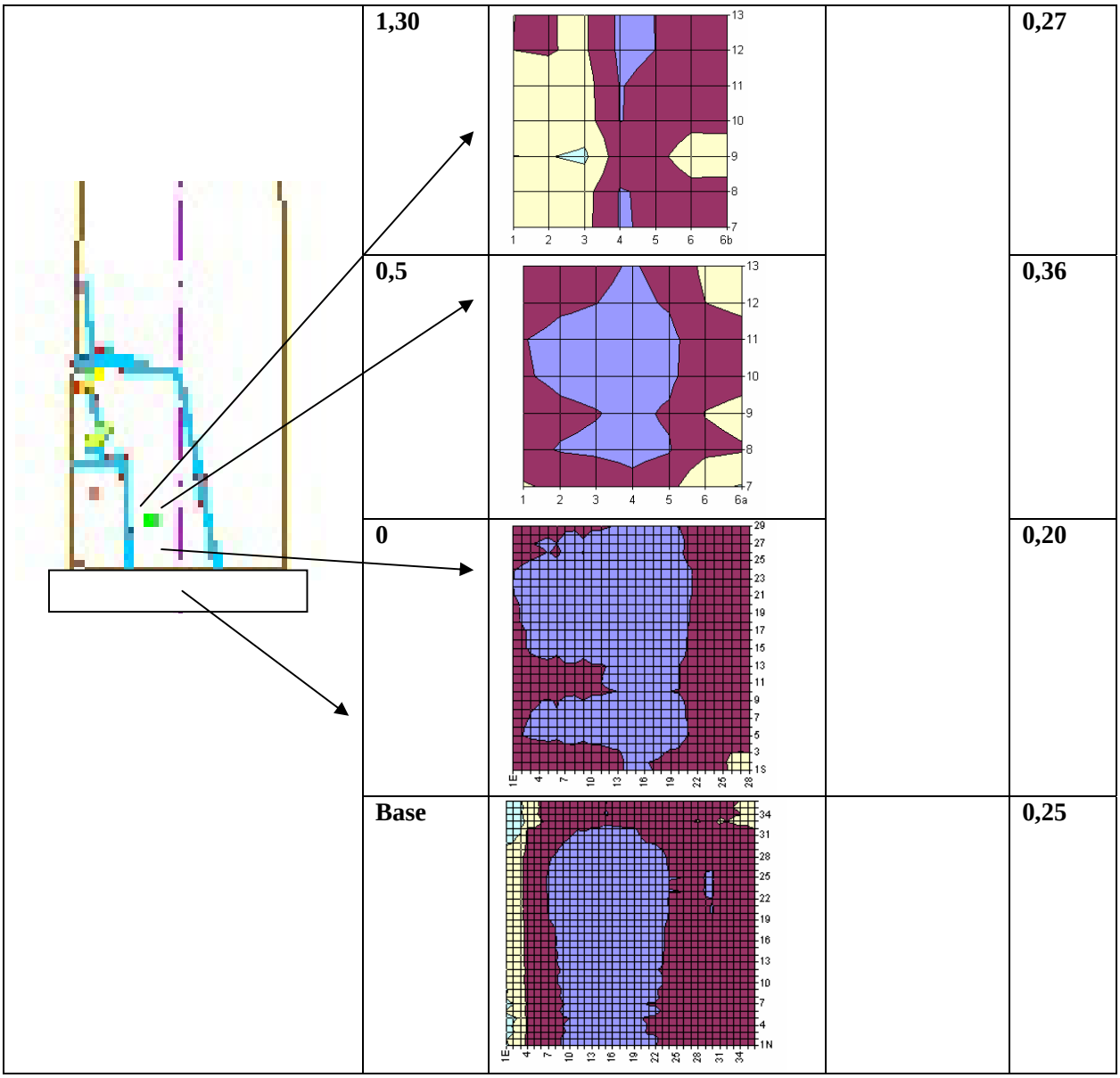


Figure 8: Sonic tomography at different levels of the obelisk

Radar investigation

The radar investigation for the Obelisk has been performed in order to evaluate the characteristics of the joints and the base. The investigation showed the following results:

- 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 roads in symmetric positions 50-50cm depth

As shown in figure 9, the periodic echoes show the metallic bars

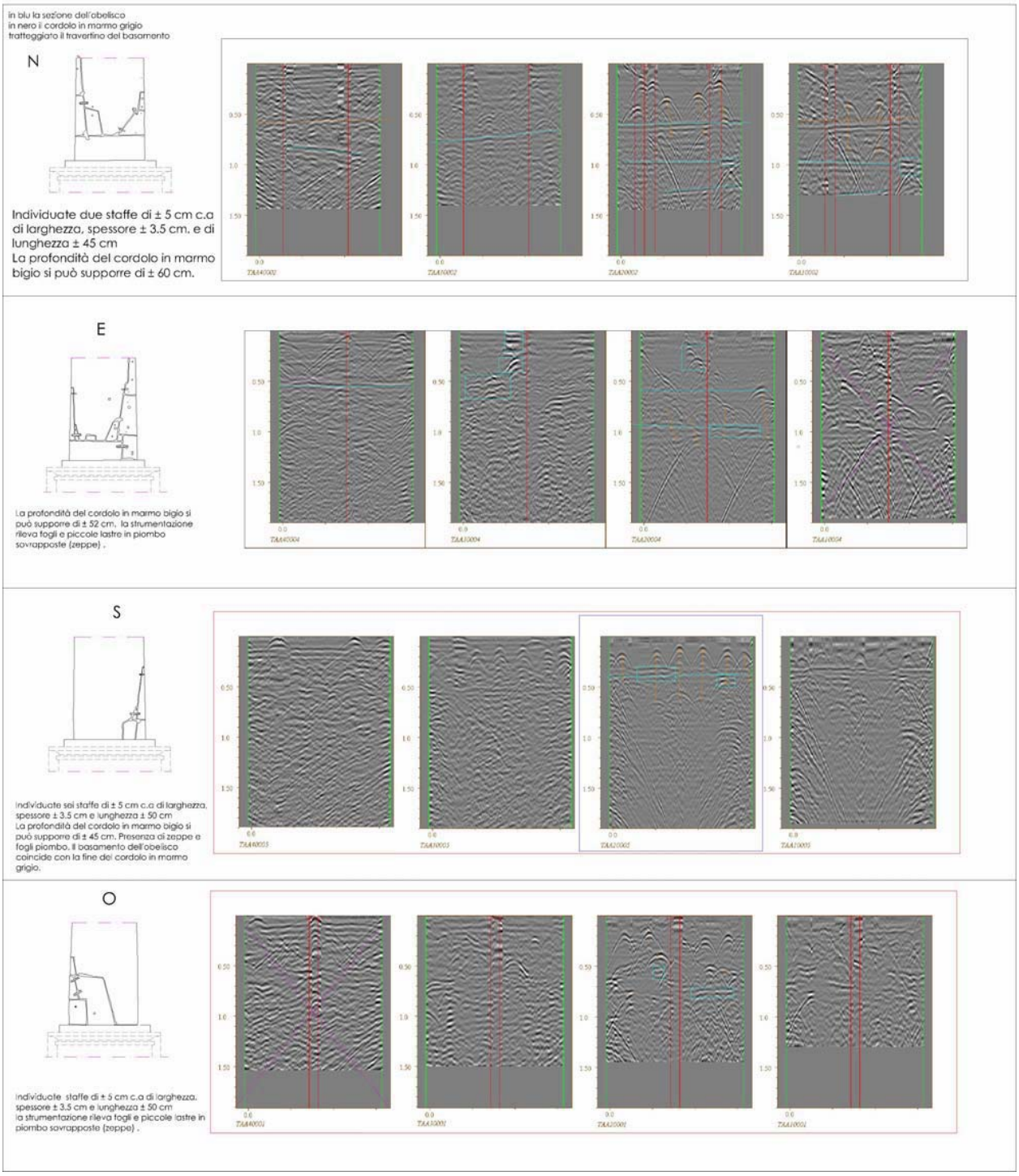


Figure 9 Radar investigation at the base of the Obelisk

Numerical analysis

Numerical analysis of the Obelisk has been performed assuming properties of the materials as given by NDT investigations and referenced to the parametric properties of granite in good conditions.

In absence of any information about the actual properties of granite, the first evaluations have been performed assuming different values of the elasticity modulus within the values of 12 GPa and 45 GPa:

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

The numerical calculations have been performed assuming the values of table N°4:

Table N° 4 Elastic modulus for the different zones

	Case 1 E[Pa]	**Case 2 E[Pa]**	**Case 3 E[Pa]**	**Case 4 E[Pa]**	**Case 5 E[Pa]**	**Case 6 E[Pa]**	**Case 7 E[Pa]**
Zone 4	1.2E+10	4.5E+10	4.5E+10	4.5E+10	3.0E+10	3.0E+10	3.0E+10
Zone 1,3	1.2E+10	1.2E+10	1.2E+9	1.2E+9	1.2E+10	1.2E+9	1.2E+9
Zone 2	1.2E+10	1.2E+10	1.2E+10	1.2E+9	1.2E+10	1.2E+10	1.2E+9

The numerical results are represented in table N° 5

Table N° 5: first 5 frequencies

	Case 1	**Case 2**	**Case 3**	**Case 4**	**Case 5**
Modo	**E=1.25E+10 Hz**	**E=2.5E+10 Hz**	**E=3E+10* Hz**	**E=4E+10 Hz**	**E=4.5E+10** Hz**
I E-W	0.81	1.15	**1.26**	1.46	1.55
II E-W	4.16	5.89	**6.45**	7.45	7.9

Critical overturning acceleration

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

a. seismic action applied at the gravity centre of the obelisk
b. seismic action distributed at the gravity centres of the blocks
c. seismic action proportional to the first two modes

Results of the calculation considering the force applied at the gravity centre of the obelisk are shown in figure 10, The critical overturning acceleration is 0.12g.

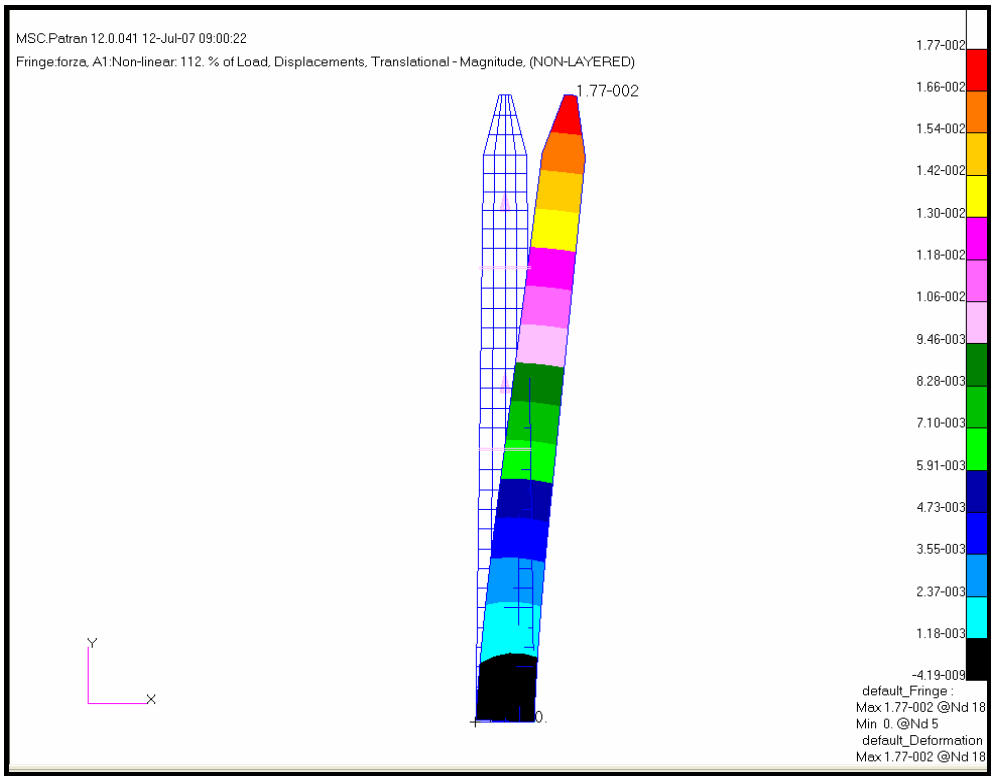


Figure 10: a) Displacements at the critical multiplier acceleration (type a forces)

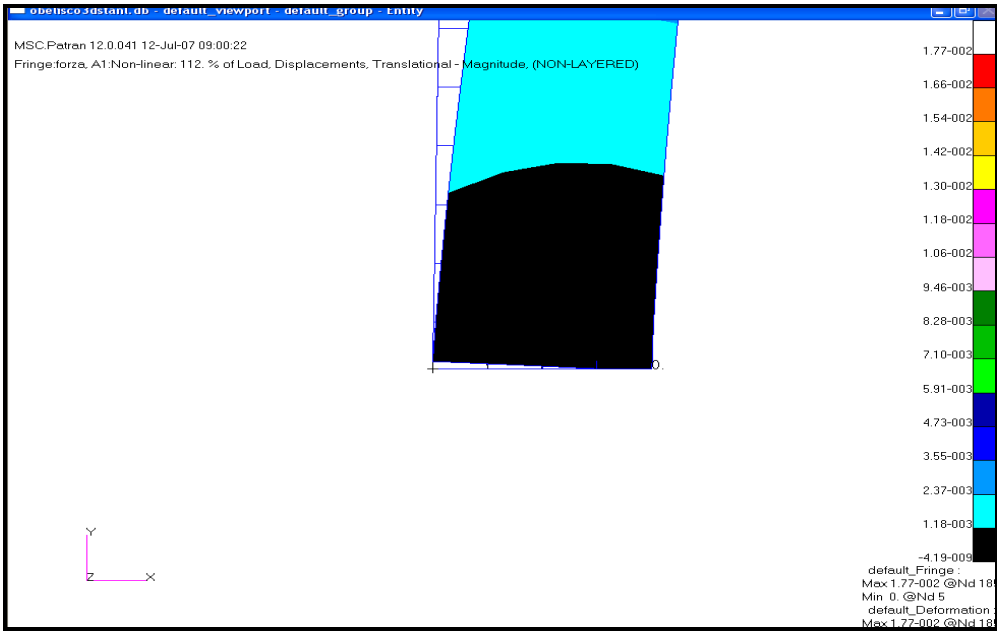


Figure 11: Zoom showing the overturning at the base (type a forces)

Considering the seismic force applied at the gravity centres of the blocks the critical multiplier value of the acceleration is 11.25% as shown in figure 12.

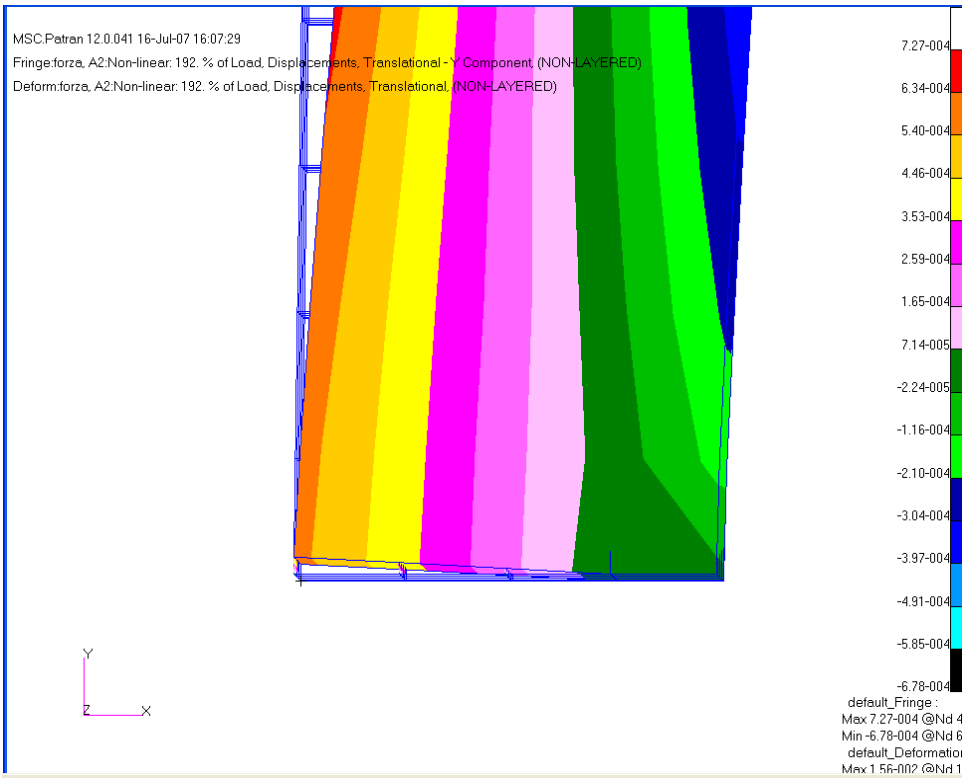


Figure 12: Overturning at 0.1125g (type b forces)

The type c seismic forces are proportional to the normalized displacements of the first two modes

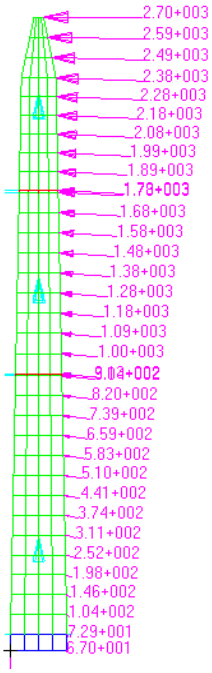


Figure 13-a: Seismic load CI

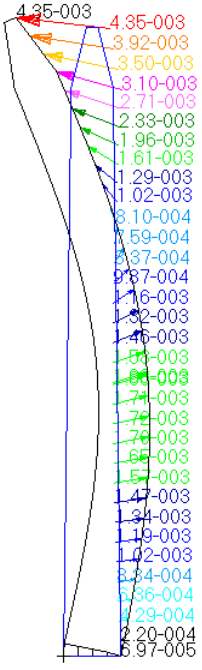


Figure 13-b: Seismic Load CII

The table N° 6 summarizes the results of the numerical simulations at different seismic loads:

Table N° 6

Seismic load:	**critical multiplier collapse factor (%)**
a : Gravity + seismic action applied at the gravity center of the obelisk	**11.25%**
b: Gravity + seismic action distribuited 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%**

Conclusions

Identification of the dynamic response of the Egiptian Obelisk of Piazza San Giovanni in Laterano in Roma,Italy has been performed by means of long term monitoring of environmental loads due to traffic and/or microseisms. Expected structural damages of this obelisk due to settlement, vibrations or earthquake actions are sliding or rocking of the three blocks of the obelisk when the horizontal inertial forces exceeding certain limits, depending on the hinges binding degree. 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. 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 the mechanical characteristics of the type 4 zones (zone with granite in good conditions), assuming different values of the mechanical properties of the zone 4 within the minimum and maximum values in literature, or each parametric value of the mechanical properties for the type 4 zone, the properties for the zone N° 1,2,3 have been modified according the sonic and radar NDT experimental results.

BIBLIOGRAPHY

[1] Marialuisa Mongelli:" Analisi agli elementi finiti dell'Obelisco Lateranense di Piazza San Giovanni in Laterano a Roma" doc. ENEA-RT-34-07

[2] G. De Canio, G. Fraraccio, M. Mongelli, N. Ranieri *"Monitoraggio delle vibrazioni naturali ed indotte dal traffico"* doc. ENEA RT-45/08

[3] A. Tatì *" Indagine diagnostica tramite esame sonico e ricostruzione tomografica dell'Obelisco di San Giovanni in Laterano-Roma"* Rapporto ENEA RT-35/07

[4] Paola Giaquinto:" L'Obelisco Lateranense: Ricerche storico-critiche e cronologia degli avvicendamenti tecnologico-costruttivi" rep. ENEA-RT-32-07

[5] Paola Giaquinto, Alessandro Colucci:" L'Obelisco Lateranense: Rilevazioni Georadar. Risultati preliminari" rep ENEA-RT-36-07

[6] G. De Canio, "Large Scale experimental facilities at ENEA for seismic tests on structural elements of the historical/monumental cultural Heritage", Proc. 9th Int. Congress on Deterioration and Conservation of Stone, Venice 19-24 June 2000

[7] G. De Canio, N. Ranieri, P. Giaquinto, M. Poggi, G. Zincone, M.L. Mongelli: Verifiche Sperimentali dei cinematismi di collasso e della propagazione del danno nei macroelementi strutturali di edifici storico monumentali: CRASC'06 Convegno Nazionale Crolli de Affidabilità delle Strutture Civili Messina 20-22 Aprile 2006

[8] G. Zingone, G. De Canio, G. Cavalieri, "On the improvement of monumental structure safety: a case study", III European Conference on Computational Mechanics Solids, Structures and Coupled Problems in Engineering Lisbon, Portugal, 5-8 June 2006 C.A. Mota Soares et al. (eds.)