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PERFORMANCE BASED ASSESSMENT OF THE OBELISCO LATERANENSE IN ROME

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ABSTRACT

The "Obelisco Lateranense" is the tallest and most damaged of the twelve Egyptian obelisks in Rome, positioned at the current location by Domenico Fontana in 1487. He connected the three large broken fragments after crash from its previous location at the Circo Maximo, where it was located by emperor Costanzo II. Therefore the structure of the obelisk must be assumed to be composed by three large heavy blocks of granite lying on each other, and at the base, by three hinges with unknown binding degree. A extensive in situ and laboratory experimental tests was carried out to identify the dynamic response of the obelisk by means of in situ monitoring of environmental loads due to traffic and/or microseisms and shaking table tests on a 1:6 reduced scale mock-up. The mechanical properties of the three hinges were assessed by recursive optimization procedure of the kinematics of the three blocks and finite element numerical model upgraded via Displacement Data Analysis (DDA). The vulnerability evaluation and seismic reliability assessment was performed adopting the methodology proposed in project PERPETUATE (www.perpetuate.eu) [1], funded by the European Commission in the 7thFramework Programme (FP7/2007-2013), under grant agreement n° 244229.

Keywords: *Obelisk, Displacement Based Assessment, PERPETUATE project, Shaking table*

1. INTRODUCTION

1.1. General information

This paper describes the in situ and laboratory Displacement Data Analysis (DDA) experimental results for seismic safety assessment of the Egyptian Obelisk located in piazza S. Giovanni in Laterano, Roma (Italy) within the framework of the Performance Based Approach (PBA). DDA is based on an innovative 3DVision system for direct measurement of the displacement field of selected structural nodal points during static and dynamic experimental tests [2]. PBA for cultural heritage assets requires proper limit states definitions which are slightly different with respect to those required for conventional civil or industrial buildings (i.e. the ASCE/SEI 41/06 specifications from US and the

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Eurocode 8 specifications from EU). In fact, in the case of single monuments like columns and obelisks, or historic buildings like churches and mosques, due to the presence of specific morphology of macro elements: rigid blocks, complex vault systems, slenderness of the walls, presence of wide halls, domes and drums with particular geometry, it is necessary to define the proper assessment procedures which are different with respect to the conventional structures. The aim of the shaking table experimental campaign was to define proper limit states and the related reference seismic input, taking into account both human life safety and specific conservation requirements (compatibility, reversibility, durability, serviceability). The limit states are correlated to proper damage measures, specifically defined for the different cultural heritage assets. Besides of in situ structural monitoring and Non Destructive Investigations, a shaking table experimental campaign on the 1:6 scaled mock-up of the obelisk has been carried out to verify its performance on the basis of the dynamics behaviours during the experimental tests.

1.2. The Egyptian obelisk at Piazza S. Giovanni in Laterano

The "Obelisco Lateranense" is the tallest and most damaged Egyptian obelisk in Rome (Italy). It was positioned at the current location of Piazza San Giovanni in Laterano in the 16th century by the architect Domenico Fontana: he made the connection of the three large fragments in which the obelisk was broken due to the crash occurred at its previous location at the Circo Maximo and the rupture in three blocks. Therefore, the actual structure of the obelisk must be assumed to be composed by three large heavy blocks of granite lying on each other, and at the base, by three hinges with unknown binding degree. Scope 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 are exceeding certain limits, depending on the hinges binding degree. The Obelisk is 32 m tall, and is composed by three blocks of granite connected each other and at the base by three joints whose mechanical characteristics have been investigated. 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. 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. Non Destructive Analyses have highlighted the ingenious system of "crux joints" realized by Domenico Fontana to recompose the three blocks and the complex and useful dislocation of the blocks of granite at the base of the obelisk [3].

2. EXPERIMENTAL TESTS ON THE OBELISCO LATERANENSE

2.1. Target performances and identification of damage measures for the Obelisk

The logical approach for PBA of the obelisk has developed in two phases:

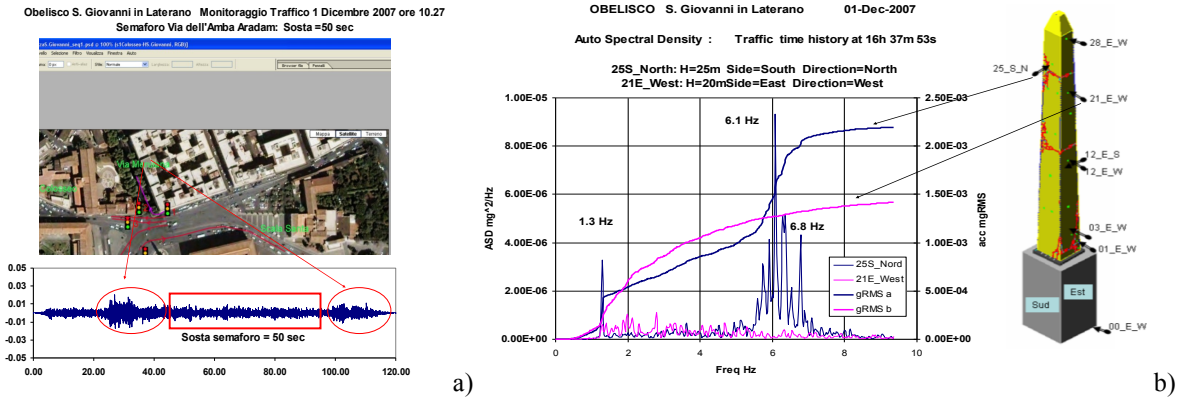
- a first phase of data input, in which the type and level of damage of the Obelisk in its constituent structural elements (the three blocks) and artistic assets (the surfaces decorations) has been identified and, for each of these, the type and level of damage has been identified too;
- a second phase where the input data have been analysed to assess the performance of the obelisk based on the shaking table tests on a 1:6 model, and the most probable mechanisms of collapse.

However, the risk level for this artistic asset is directly correlated to the risk of collapse of the rigid blocks due to slide and overturning, therefore the scope of the experimental tests was to verify the kinematics of the blocks at different hazard level of the seismic input at the base of the shaking table. Once identified the most probable mechanisms of collapse, the experimental campaign has been carried in three phases to assess the performance level:

- in situ structural monitoring and dynamics characterization by ambient vibrations;
- in situ Non Destructive analyses for mechanical characterization of the material and validation of the numerical model.
- Laboratory Shaking table experiments
- Validation of numerical models and Rocking spectra evaluations

2.2. Dynamics characterization by ambient vibrations and seismic monitoring

Ambient traffic vibrations have been recorded, at different daytime, for six months: early in the morning, heavy midday traffic and low late night traffic. The traffic in the obelisk zone is regulated by 4 traffic lights; at each green light there is at least one heavy truck or bus. The accelerometer sensors have been positioned at the points of the Obelisk where the original holes were present.



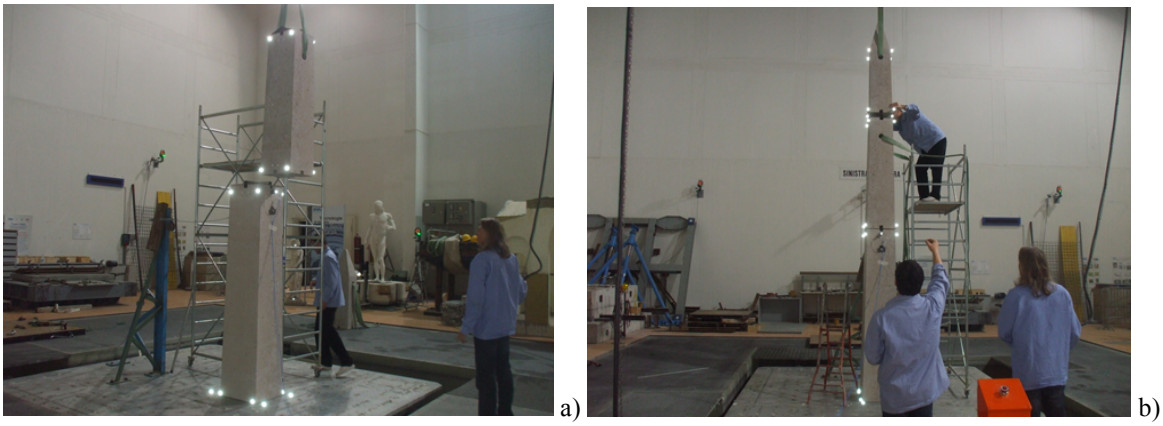
a) b)

Fig. 1 In situ monitoring: a) traffic induced accelerations, b)Power Spectral Density and Frequency contribution to the RMS acceleration value (in cm/sec^2) of the accelerations 21E_west and 25S_North.

The frequency contribution to the RMS acceleration at different levels of the obelisk are shown in fig.1, with peaks at 1.3 Hz and 6.1 Hz corresponding to the principal components of the Obelisk in the elastic phase. The figure shows also the location of the accelerometers, the sensor identification has the following format: Level_Face_Orientation (e.g. 28_E_W means: level= 28, Face = East, orientation=West). For the seismic monitoring two free-field velocimeter surveys were carried out close to the Obelisk, in order to analyse the local seismic response and to characterize possible ground motion amplification effects [4]. Records of ambient noise were obtained in 2 temporary stations respectively located about 10 m S and 30 m SW of the Obelisk Each station was instrumented with 3 velocimeters SS1, 3axes arranged. The acquisition was performed early in the morning with the aim of reducing the disturbance due to street traffic. No relevant difference has been observed between NS/UP and WE/UP ratios therefore mean HVSRs are considered. The values of the spectral amplitudes result to be related to the traffic noise level rather than the location of the measurement, the lower levels being observed in the nocturnal records with reduced traffic. The analysis of ambient noise recorded at both ground level and underground has not pointed out amplification effects near by the Obelisk.

2.3. Shaking table tests

A 1:6 reduced scale mock-up of the obelisk, with the same hinge connections between the blocks designed by Domenico Fontana has been realized. As the original obelisk, the mock-up is not base symmetric and the geometry of the hinges does not allow sliding, therefore combined multi directional rocking is present for this structure. The obelisk mock-up has been subjected to the following series of shaking table tests at the ENEA Casaccia laboratories of Roma, Italy: pull release, one directional and three directional earthquakes, one directional and three directional pulse. The tests have been performed on the single block, double blocks and three blocks configuration. The displacement data have been recorded by means of a new, innovative, high resolution 3-D optical movement detection and analysis tool named “3DVision”, tracking the dynamic displacement of special markers positioned at selected points of the structures during the shaking table tests. Fig. 2 shows the positioning of the obelisk mock-up on the shaking table, the light spots at the corners of each block are the retro reflecting markers for 3DVision-DDA located at selected FEM (Finite Element Model) nodes.

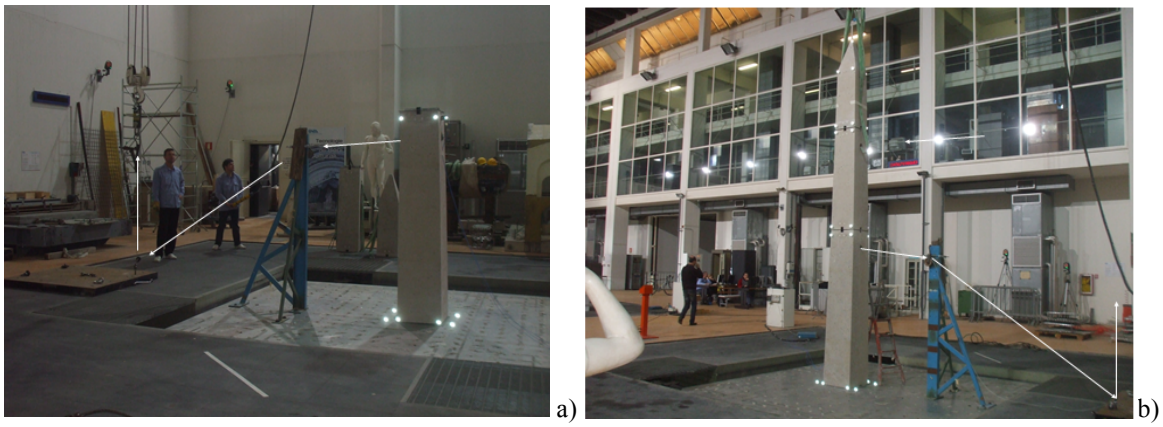


a) b)

Fig. 2 Positioning of the three blocks of the obelisk on the shaking table for the seismic tests

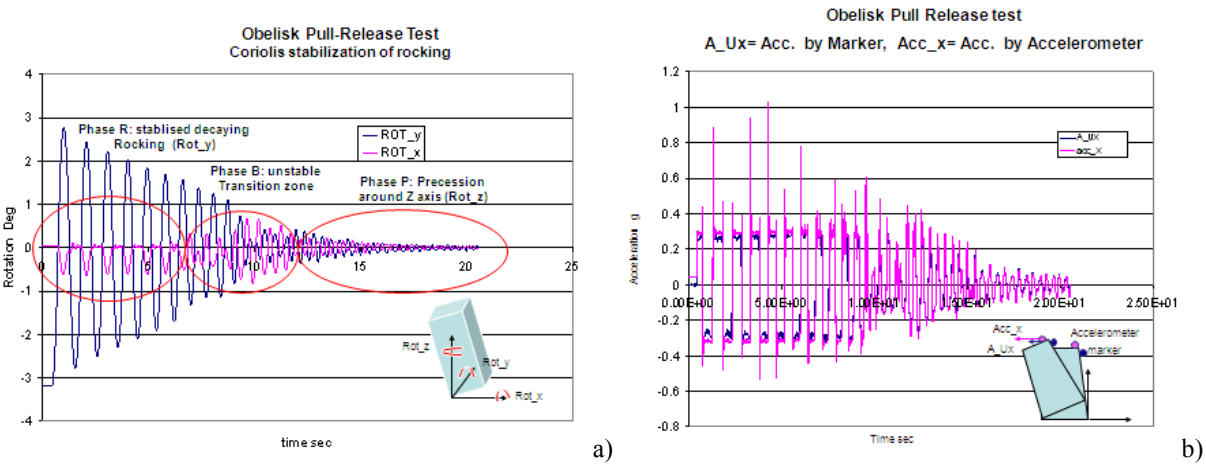
2.3.1. Pull Release tests

A series of pull release tests have been performed to characterize the rocking dynamics of the single, double and three blocks of the obelisk. The test set-up for these series of tests is shown in fig. 3.



a) b)

Fig. 3 Pull release test the ENEA Casaccia laboratory of Roma, Italy: a) single block, b)three blocks obelisk.



a) b)

Fig. 4 Pull release test: a) 3DVision-DDA identification of zones R,T, P; b) comparison between accelerations by 3DVision-DDA (blue) and traditional accelerometer (magenta) during the R,T and P phases.

The pull release test results by 3DVision-DDA identify three well-defined phases in the dynamics of the obelisk: R (rocking), T (transition), P (Precession).

- Phase R: Stable yet decaying rocking around Y axis (Rot_y), in which the rotation around Y axis is prevalent with respect to the rotation around X axis;
- Phase T: Unstable Transition phase, activated at a critic angular velocity, in which the rotation around X axis becomes more significant and is comparable with the rotation around Y axis;

- Phase P: Stable yet decaying Precession phase, where the dynamic of the block is characterized by the prevalent precession around Z.

The RTP phases are evident in the rotation angle time histories of fig. 4a. The fig. 4b shows the accelerations recorded by the accelerometer at the top of the first block and its companion marker.
During the phase R the obelisk half rotates around X axis (fig. 5a, Rot_x) with persistent negative maximum peak values of the rotation angle. It is also notable, during phase R, the persistence level of the impact acceleration peaks in fig. 5b. However, the impact spikes due to elastic waves recorded by the traditional accelerometer are not present in the marker 3DVision-DDA acceleration.

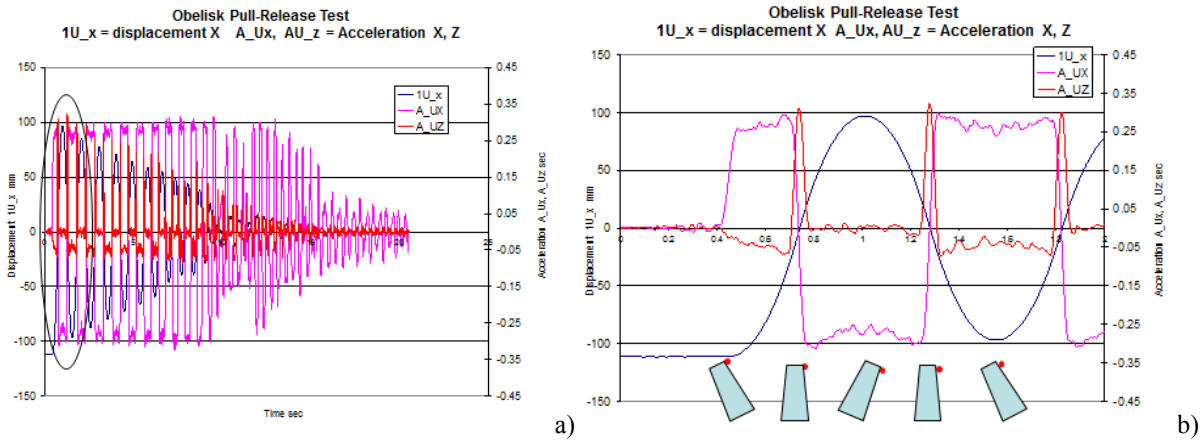


Fig. 5 Comparison between accelerations measured by markers (blue) and accelerometer (magenta). a) complete time history comprehensive of phase A, phase B and phase C; b) zooming window of one R phase period

The RTP phases are also evident in the 3DVision-DDA X displacement (1U_x, blue), X acceleration (A_Ux, magenta) and Z acceleration (A_Uz, red) of fig. 5a. The zooming of one period of phase R is shown in fig. 5b with well-defined *not decaying* horizontal and vertical components of the accelerations together with the *decaying* displacement. The pull release 3DVision-DDA for the three block obelisk are shown in fig.6.

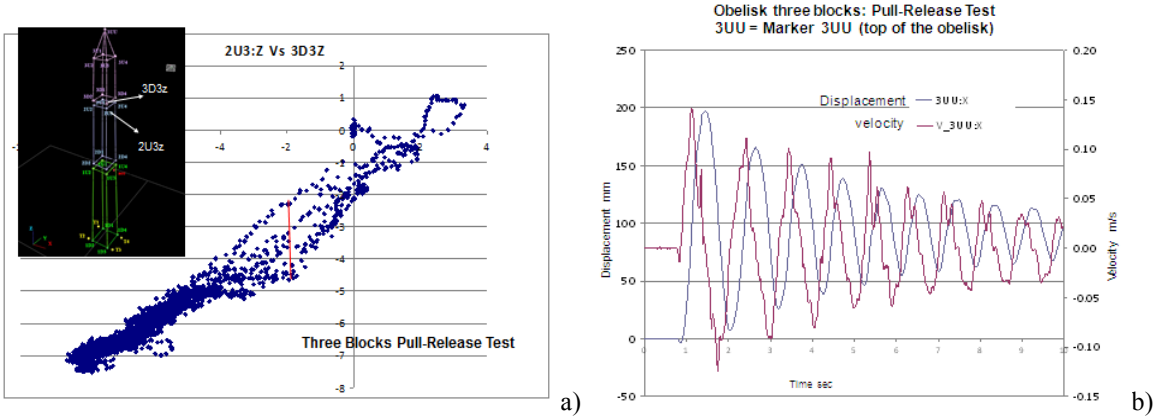


Fig. 6 Three block pull release test: a) difference (drift) of second and third blocks by 3DVision DDA , b) displacement and velocity at the top of the obelisk

The second and third block drifts during the test are showed in fig. 6a, the fig. 6b shows the displacements and velocity time histories at the top of the obelisk. The velocity and displacement plot in fig. 6b also show the secondary impacts between the adjacent blocks.

2.3.2. Seismic tests

The seismic X,Y,Z time histories for the numerical simulations and shaking table tests are those equivalent to the maximum hazard for the site of the obelisk. They have been defined according to the new hazard maps for the 6 municipality groups and their associated Uniform Hazard Response

Spectrum (UHRS) of the Lazio Italian Region [5] where the municipalities of Roma are grouped in two seismic zones. The natural acceleration records for the UHRS procedure were selected according to the return period of 2475 years for safety assessment of monuments in the municipality where the Obelisk is located. The selected records are those of the November 23, 1980 Campania and Lucania earthquake at Arienzo obtained for a return period of 475 and the same for a return period of 2475 years and from those obtained by applying the same methodology LEMA_DES [6]. The obtained time-histories were filtered taking into account the shake-table displacement limits (PGD < 12.5 cm). The pulse time histories, representative of the main seismic pulses have been derived by the same procedure. The full scale time histories relative to the obelisk site were scaled according to the mechanical similarity studies for real and scaled structures.
The geometrical properties of the 1:6 scaled model of the obelisk are described in Table 1. Blocks number 1 and 2 are shaped like a truncated pyramid, while the third one has also a pyramidal top (see Fig. 2 and 3).

Table 1. Dimensions of the three blocks that compose the obelisk.

	Block 1	Block 2	Block3	Total
Lower base b_L [m]	0.48 – 0.5	0.39 – 0.43	0.33 – 0.385	
Upper base b_D [m]	0.39 – 0.43	0.33 – 0.385	0.29 – 0.355	
Height h [m]	2.35	1.568	1.469	5.387
Volume [m^3]	0.479	0.231	0.137	0.847
Centre of gravity G [m]	1.106	0.598	0.5	2.145

In order to evaluate the displacement capacity of the structure through the capacity curve [7], the following parameters have been calculated: the equivalent block slenderness, equal to $\lambda=2G/b=8.94$; the overturning spectral acceleration, equal to $a_0=g/\lambda=1.098$ m/s^2; the displacement capacity equal to $b_{L(1)}/2= 0.24$ m. In Fig. 7a the capacity curve of the rigid block is depicted by red line.
On the base of the response to pull release tests different aspects have been evaluated: - the period corresponding to different amplitude of motion; - the experimental capacity curve; - the damping of the system. It can be observed that a good agreement is achieved between the experimental (Fig. 7a, black dot line) and rigid block model capacity curve in correspondence to great oscillations, while subsequently (for small oscillations) the system shows an elastic behaviour, with an elastic period of vibration equal to T=0.91 s (Figure 7a, blue line). Consequently, the non-linear dynamical model is assumed as a bilinear curve (continuous line).

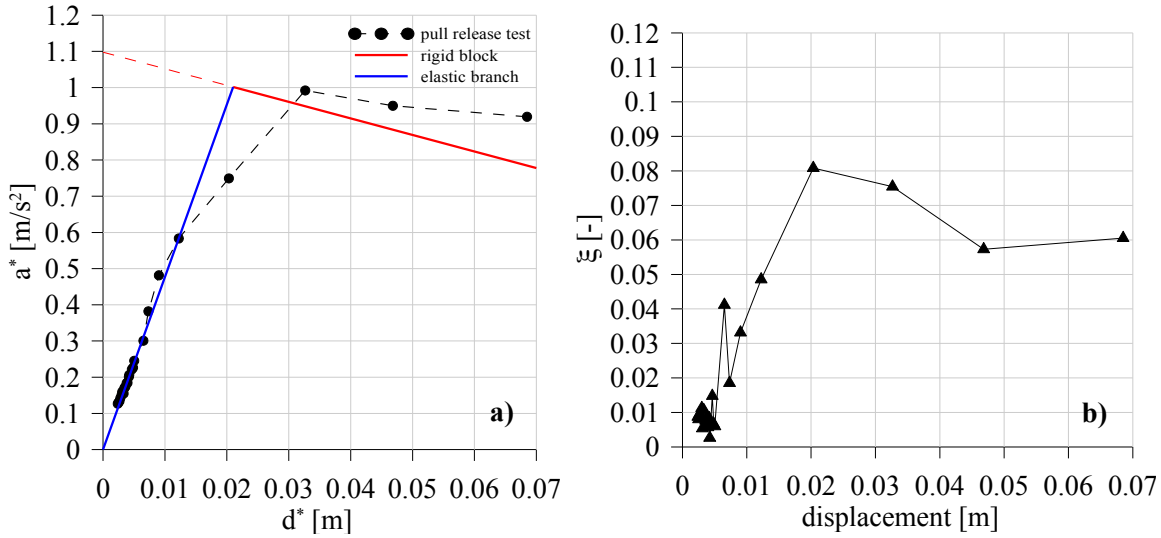


Fig. 7 a) Comparison between experimental and theoretical capacity curve. **b)** Damping evaluation from pull and release test.

The damping ξ has been evaluated by considering the logarithmic decay during the pull release tests. Figure 7b shows the results: it can be observed that in correspondence to the rocking behaviour, the range of damping values is from 6% to 8%, while it greatly decrease to less than 1% in the elastic branch.

The time histories for the shaking table tests have been scaled increasing value of PGA thus performing an experimental Incremental Dynamic Analysis, in particular five PGA have been considered: 0.04 g, 0.06 g, 0.08 g, 0.1 g and 0.13 g. The resulting measured PTA (Peak Table Accelerations) have been: 0.0525 g, 0.082 g, 0.107 g, 0.134 g and 0.18 g. The spectral accelerations and displacements have been evaluated considering a damping equal to 5% for the first three time histories (0.04-0.06-0.08 g), to 6% for the fourth (0.1 g) and 7% for the last (0.13 g).

Fig. 8 shows the comparison between the experimental displacements at the centre of gravity of the obelisk corresponding to 0.13 g input and the numerical ones. In Fig. 8a and 8b the response obtained by the bilinear model and by Housner model are depicted, respectively. The first one is in good agreement while the second isn't absolutely comparable.

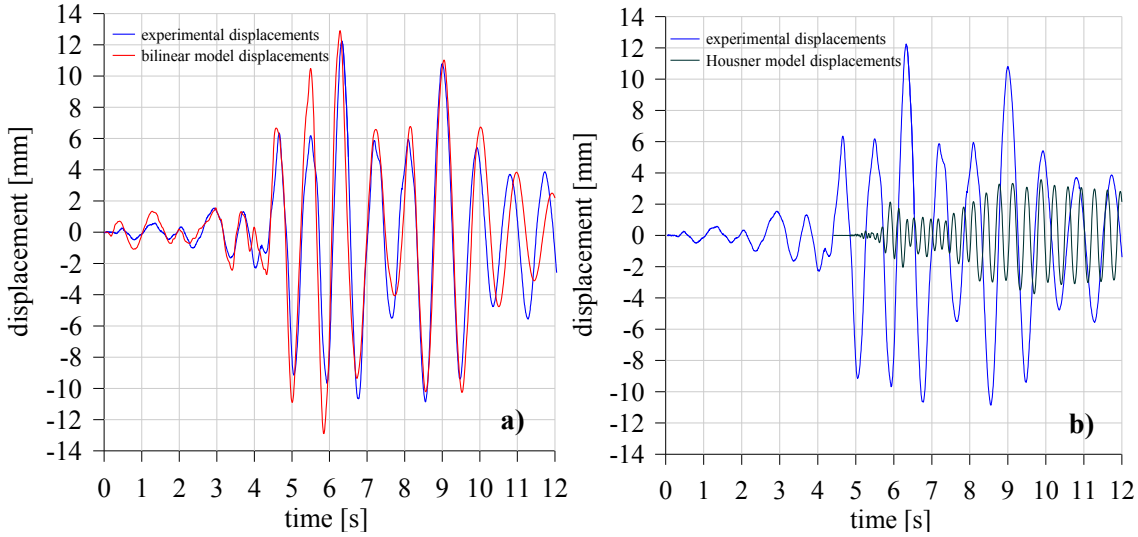


Fig.8 Comparison between experimental and numerical results ((a) bilinear, (b) Housner).

In Fig. 9a, the input is represented in the spectral acceleration/displacement form, together with the capacity curve of the structure. It can be observed that the intersection between the capacity curve and the spectral acceleration/displacement form, that represents the displacement demand (performance point), is always near to the maximum displacements value recorded on the structure; it is important to notice that these values are always in the elastic phase of the structure, thus far away from collapse point. This comparison is effectively represented by the curve of fig. 9b, that shows the results of the Incremental Dynamic Analysis. For each time history, the maximum horizontal displacement achieved on the centre of gravity of the obelisk is plotted as a function of the nominal PGA applied. Moreover, the theoretical displacements calculated at the performance point and the maximum spectral displacement demand are plotted [8]. It can be observed that the linear trend of the curve confirms the distance from structure collapse.

Fig. 10a shows the comparison between capacity curve and the acceleration/displacement spectra scaled to 0.6 g, corresponding to the hypothetical collapse spectra, in order to obtain a maximum spectral displacement demand equal to 40% of the maximum displacement capacity of the structure (d_u=0.096 m). In Fig. 10b the related displacements obtained by the bilinear model and Housner one are compared. It can be observed that in correspondence of great displacements the curve are more in agreement than in the case of lower ones, because of different behaviour of the two considered models during small displacements (rigid the first, elastic the other one).

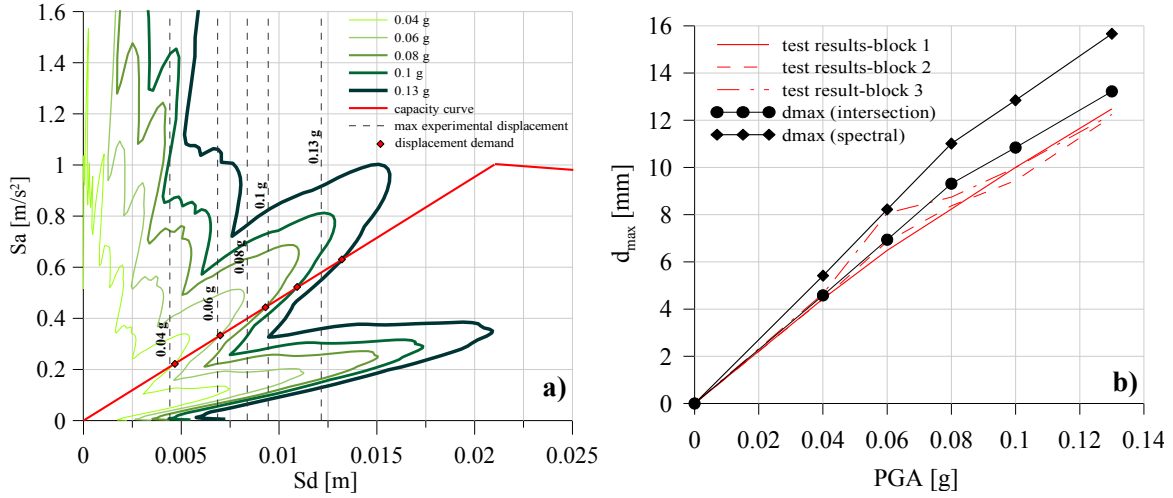


Fig.9 a) Acceleration/displacement spectra vs. capacity curve of the obelisk. **b)** Incremental Dynamic Analysis (IDA) of the obelisk.

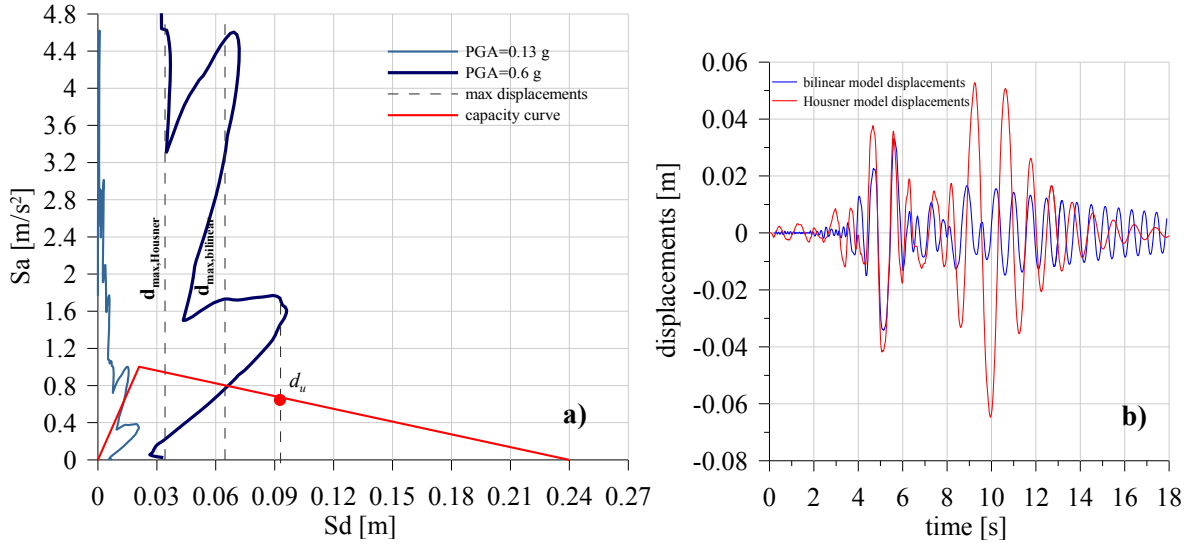


Fig.10 a) Collapse spectra vs. capacity curve. **b)** Comparison between the displacements obtained by bilinear model and Housner one corresponding to the application of collapse input (PGA=0.6 g)

2.4. Rocking spectra

The dynamic response of the obelisk to earthquakes, as a free-standing block, is strongly non-linear and depends essentially on the critical angle α, the frequency parameter P and the spectral shape and intensity of the ground acceleration time history. A parametric study of the dynamic response of the obelisk to earthquake, constant sine, Pulse A, B, C, D [9] has been performed through numerical integration of the (non-linear) equation of the rocking motion in presence of horizontal ground acceleration:

$$\ddot{\theta}(t) + p^2 \sin(sig(\theta)\cdot\alpha - \theta(t)) = \frac{\ddot{u}(t)}{g}\cos(sig(\theta)\cdot\alpha - \theta(t)) \qquad (1)$$

Where *u(t)* and g are the horizontal and gravity accelerations [10], the numerical model has been validated by 3DVision-DDA during the shaking table tests. The rocking pulse spectra and rocking seismic spectra obtained by numerical integration of eq. (1) are shown in fig. 9 and 10. The sine test numerical results in fig. 11 show the acceleration and velocity singularities at the rocking impacts.

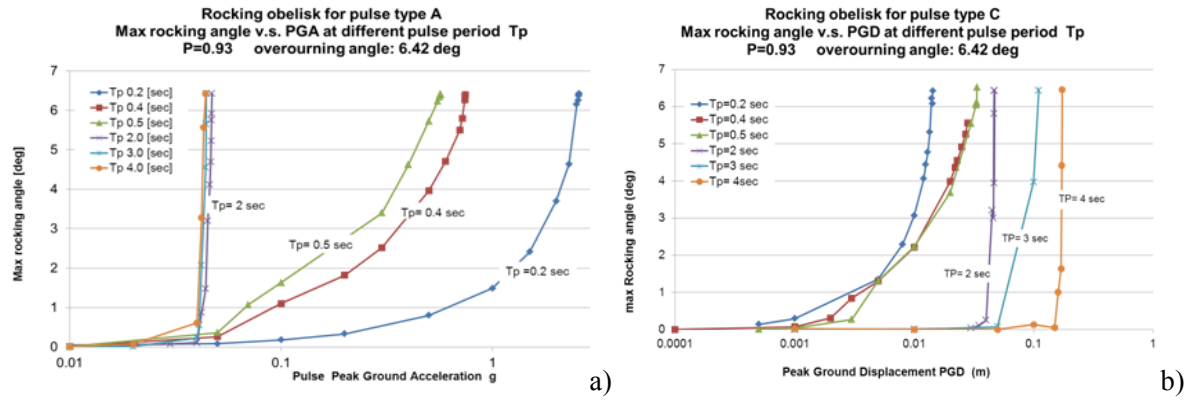


Fig. 9 Parametric analysis of demand spectra for pulse A and C: a) Pulse type A, max Rocking angle V.S. PGA at different pulse period, b) Pulse type B, max Rocking angle V.S. PGA

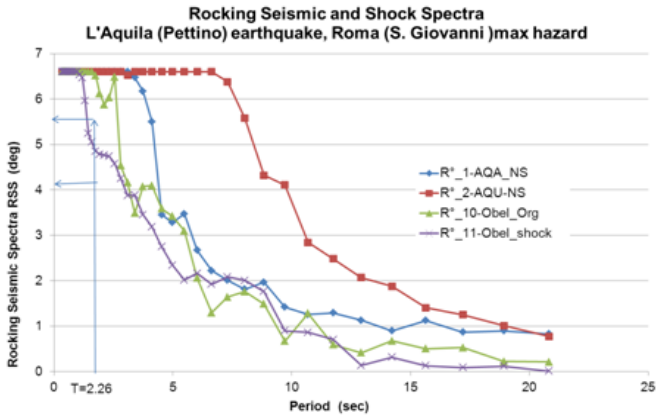


Fig. 10 Rocking Spectra for L'Aquila (Pettino), Roma (S. Giovanni) max hazard and its main seismic pulse

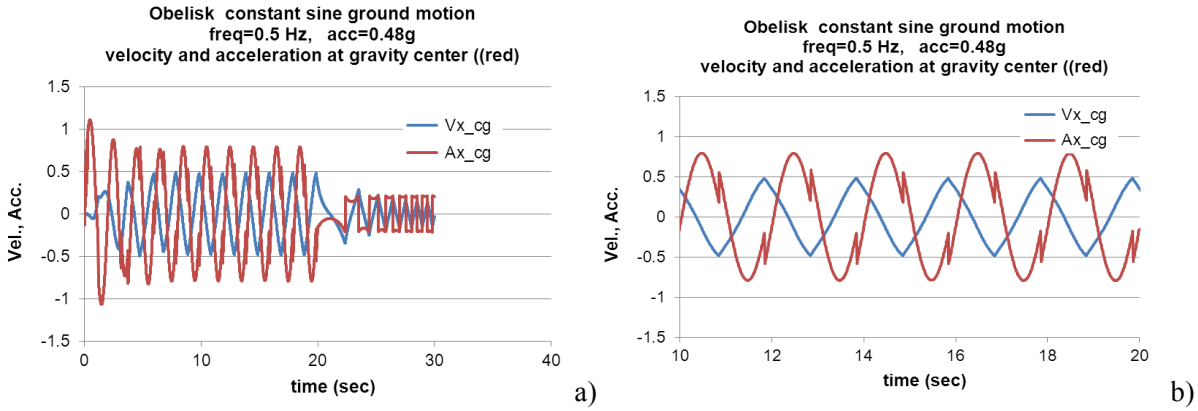


Fig. 11 Constant sine test frequency 0.5 Hz, Acc.=0.48g: a) 20 sec duration of base motion followed by 10 sec free rocking , b) Velocity and acceleration signatures of the Rocking impacts

3. CONCLUSIONS

Displacement Data Analysis (DDA) within the framework of the Performance Based Approach (PBA) have been used for seismic safety assessment of the Egyptian Obelisk located in piazza S. Giovanni in Laterano, Roma (Italy) by shaking table experimental tests. The DDA has been based on an innovative 3DVision system for direct measurement of the displacement field of selected structural nodal points during static and dynamic experimental tests on cultural heritage assets and macro elements. The experimental tests were performed on a 1:6 scaled mock-up of the obelisk and the numerical model was validated by the 3DVision displacement data.

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