



ON THE MITIGATION OF THE SEISMIC RISK OF ART OBJECTS: CASE-STUDIES

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SUMMARY

In surveys related to the prevention of seismic damage particular attention has been paid to the safeguard of historical, artistic and monumental buildings. Nevertheless, the same attention has not been paid to the problems related to the seismic protection of art objects and museum contents. In many cases the seismic behavior of art objects can be analyzed within the context of the dynamic response of rigid blocks under seismic loads. In the paper, assuming the art object as a rigid body, the seismic vulnerability of some classes of art objects has been investigated. Namely the seismic behaviors of ancient Greek vessels as well as of stone statues have been analyzed with reference to different seismic loading. Furthermore, the behavior of the same objects subjected to base isolation has been simulated in order to verify the efficiency of the safeguard measure considered.

INTRODUCTION

The past and the recent seismic events clearly showed the high vulnerability of art objects and of museum contents also for moderate earthquakes. However, in the studies on the prevention of seismic damage, a marginal attention has been paid, so far, to the problems related to the safeguard of art objects that, in most cases, have an inestimable value and represent a common heritage that must be protected. From a structural point of view, the seismic behavior of art objects in many cases can be analyzed within the context of the dynamic response of rigid blocks under seismic loads. In the literature there is a wide number of analytical studies on the non linear dynamics of the rigid block, starting from the pioneering work by Housner in 1963 [1]. However, to the authors knowledge, the first paper that explicitly relates to the safeguard of art objects against earthquakes is due to Agbabian et al. [2] in 1988. The study was developed within a research project sponsored by the Jean Paul Getty Museum in Malibu, California. In the paper some analytical and experimental techniques are combined in order to evaluate the mitigation effects for different categories of artifacts. Recently, in Italy, some research groups have carried out a systematic study on this subject, underlying the problem to the attention of the scientific community. Augusti et al. [3, 4, 5] and Ciampoli et al. [6, 7] have studied the seismic behavior of museum contents and the reduction of the risk of damaging effects giving some simple rules for the design of display cases and other means of exhibition. Vestroni and Di Cinto [8] have studied the response of an isolated statue modelled as a single degree of freedom system characterized by a hysteretic force-displacement law for

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the isolator. More recently, the present authors analyzed theoretically the passive control of the vibrations of art objects on a particular base isolated support, through the introduction of a plane non linear model [9]. The considered structural model consists of a symmetric rigid block simply supported on a movable mass support connected to a visco-elastic device in order to determine a passive control system.

With reference to the practical applications, in Italy there are some extremely important examples of seismic protection of art objects by means of base isolation [10]. Namely, base isolation systems with laminated rubber bearings have been designed and realized for the *Bronzes of Riace* (figure 1a), for the statue of the *Satyr of Mazara del Vallo* (figure 1b) and for the statue of the *Imperatore Germanico* (figure 1c). While the seismic protection of the statues of *Neptune* (figure 1d) and *Scilla* (figure 1e) has been realized by means of supports constituted by steel and Teflon[®] and dampers made of shape memory alloy steel.

The aim of this paper is to investigate the seismic vulnerability of some classes of art objects and to evaluate the efficiency of the seismic isolation as a measure for the mitigation of the seismic risk. Namely the seismic behaviors of ancient Greek vessels as well as of stone statues have been analyzed with reference to different seismic loadings. The art objects have been considered as rigid blocks simply supported on a rigid base. The applications have been performed considering the large displacements kinematics but considering only the rocking behavior of the object according to the *simple rocking model* [11]. Furthermore, the behaviors of the same objects on a base isolation system have been simulated, according to the model proposed by the authors in [9], in order to verify the efficiency of the base isolation as a safeguard measure for the mitigation of the seismic risk of art objects.

THE SEISMIC VULNERABILITY OF ART OBJECTS

In order to assess the seismic risk of an art object, it is reasonable to assimilate the object to a rigid body and therefore to investigate the dynamics of such a structure according to the widely, but not exhaustively, investigated nonlinear dynamics of the rigid block.

In this study the attention is focused on the behavior of the simple rocking model [11], therefore it is assumed that the motion is two-dimensional and that the block is always in contact with the base.

The limits of these assumptions are clearly explained in the quoted paper. According to the simple rocking model, the behavior of the object under seismic loading may be classified in the following cases:

- object in full contact with the base;
- a finite number of phases of rocking and re-contact;
- a finite number of phases of rocking followed by overturning.

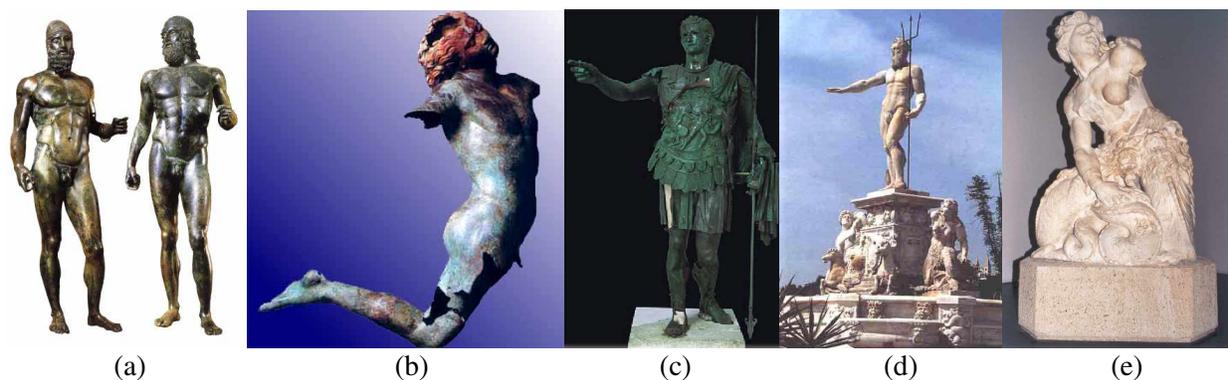


Figure 1. Some examples of seismic isolation of art object: (a) *Bronzes of Riace*; (b) *Satyr of Mazara del Vallo*; (c) Statue of the *Imperatore Germanico*; (d) Statue of *Neptune*; (e) Statue of *Scilla*.

The first case is trivial. In the other two cases the rocking phases are governed by the equation of motion of the rigid block under seismic excitation:

$$\left(mr^2 + I_o \right) \ddot{\vartheta} + m \left(h \cos \vartheta \pm b \sin \vartheta \right) \ddot{u}_g - m \left(h \sin \vartheta \mp b \cos \vartheta \right) \left(g + \ddot{v}_g \right) = 0 \quad (1)$$

This equation is referred to a symmetric block of base $2b$ and height $2h$, mass m and rotational inertia about its centroid I_o , simply supported on a rigid base. \ddot{u}_g is the horizontal ground acceleration, \ddot{v}_g the vertical ground acceleration, g is the gravity acceleration and ϑ is the angle of rotation of the block (figure 2). In equation (1) the double signs are relative to the cases of rocking about the right corner (upper sign) and about the left corner (lower sign). In order to evaluate the dynamic response of the object under earthquake loading, the transition conditions between the different phases of motion must be clarified.

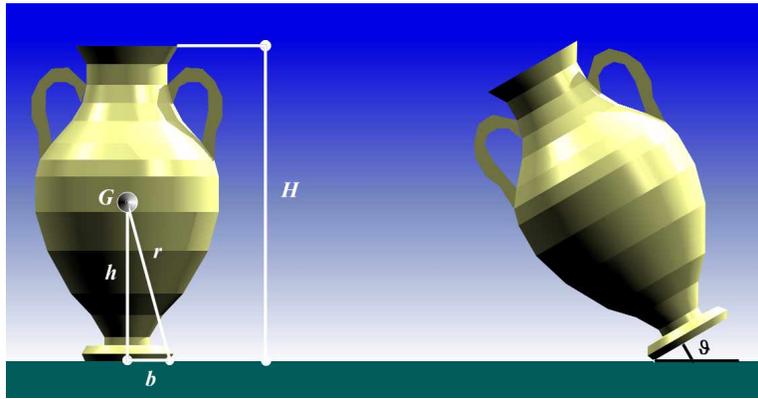


Figure 2. The considered model.

The incipient rocking condition

The object begins to rock when the overturning moment due to external loads attains the available resisting moment owing to the forces associated with gravity and with the vertical support acceleration. This condition may be written as

$$\left| \ddot{u}_g \right| = \frac{b}{h} \left(g + \ddot{v}_g \right) \quad (2)$$

The impact conditions

Regarding to the definition of the impact conditions, it is important to take into account the fact that after an impact the system may either rock again or remain in contact with the base; furthermore, in the case of rocking, the object can either rock about the impacting corner or about the contact corner (bouncing). In the following a simplified formulation is particularized with reference to the simple rocking model for which the sliding of the object is prevented. The impact is considered as instantaneous, therefore the velocities will vary instantly, while the positions of the object and the support will not change during the impact. A superscript ‘-’ will be used to characterize a pre-impact quantity while a superscript ‘+’ will identify a post-impact value.

Regarding the dissipation of energy associated to the impact, it has been assumed that this occurs as a perfectly inelastic collision with complete dissipation of the vertical momentum. This simplified assumption has already been assumed in similar studies in the literature [13]. If after the impact the object

re-uplifts, the dissipation of the vertical momentum leads to the following condition for the rotational velocity of the object

$$\dot{\vartheta}^+ = \pm \frac{h}{r} \dot{\vartheta}^- \quad (3)$$

where the positive sign must be considered when, after the impact, the object rocks about the other corner (impacting corner), while the negative sign relates to the case of bouncing, i.e. the object tilts about the same corner (contact corner). These two types of behavior are sketched in figures 3a and 3b, in which the pre-impact and post-impact linear and angular momenta acting on the object are qualitatively visualised. Without lack of generality, assuming that the object approaches the support by rocking about the right corner, it will uplift by rotating about the left corner if the following condition is satisfied

$$mh^2 \dot{\vartheta}^- + I_o \dot{\vartheta}^- > mb^2 \dot{\vartheta}^- \quad (4)$$

this yields to the inequality

$$\lambda > \frac{1}{\sqrt{1+\gamma}} \quad (5)$$

in which the dimensionless parameter $\gamma = I_o / mh^2$ has been introduced. It is worth to notice that the condition (5) is associated only to the geometry of the object and mainly to the geometrical ratio h/b . It is evident that squat objects are more prone to bounce while slender objects will re-uplift about the impacting corner.

Furthermore, in order to evaluate whether after the impact the object will remain in a full contact phase or will re-uplift about one of its ends, the overturning moment M_o and the resisting moment M_s should be compared, thus the object will not begin a new phase of rocking if the following condition is satisfied

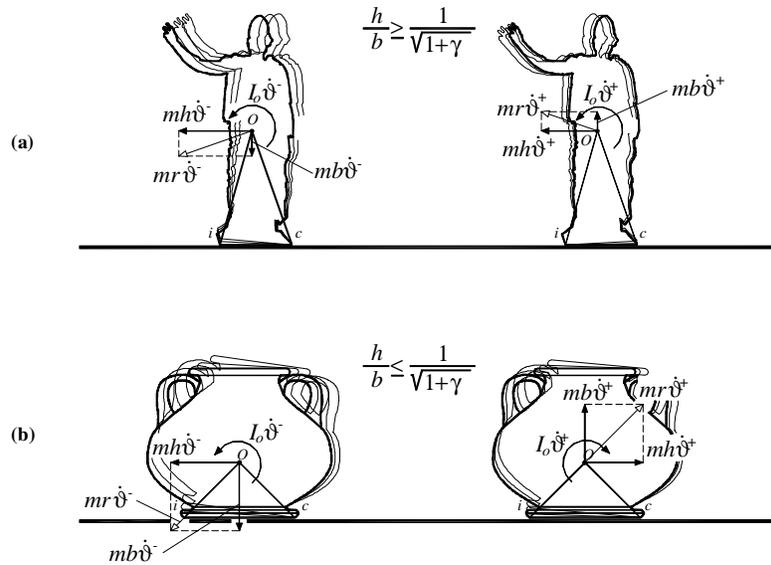


Figure 3. Pre- and post-impact conditions; (a) case of rocking about the impact corner; (b) case of rocking about the contact corner.

$$|M_s| > |M_o| \quad (6)$$

Numerical evaluation of the seismic vulnerability of some classes of art objects

The applications reported in the following refer to some classes of art objects without any measure of seismic protection. In the analyses two seismic excitations have been considered: the North-South component of the ground acceleration recorded at Sepolia during the 1999 Athens earthquake, and the North-South component of the ground acceleration recorded at El Centro during the 1940 Imperial Valley earthquake, reported in figure 4.

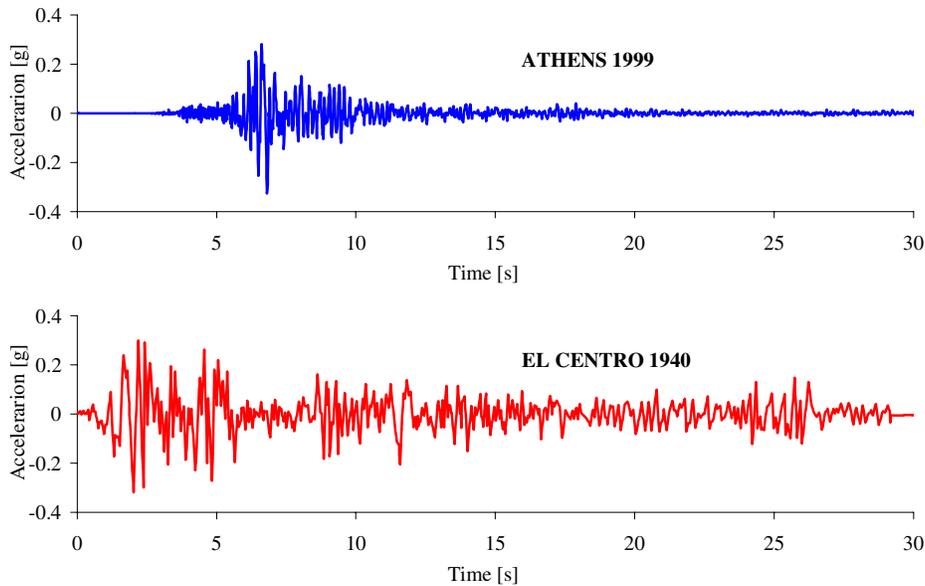


Figure 4. The considered ground motions.

Amongst the wide panorama of art objects, in this study the attention is focused on some typical examples of Greek vessels and stone statues representing human figures. This choice can be justified by the fact that many of these artifacts were destroyed or subjected to severe damage during past seismic events. The problem is extremely felt in the museum circles, so that the first research on the topic was started by the Jean Paul Getty Museum in Malibu California [2].

Greek vessels

The Greek vessels can be classified in several typologies according to their shapes and sizes. In this study four classes have been selected and investigated in detail. These are: the *amphora*, the *volute krater*, the *kylix* and the *lekythos*; most museums all around the world, as well as private collectors, have many examples of these vessels of various sizes and decorations. In figure 5 some examples of these vessels are reported.

In the ancient Greece the amphora (figure 5a) was used to carry liquids, the lekythos (figure 5d) was utilized for pouring, the kylix (figure 5c) was mainly used for drinking, while the krater (figure 5b) was employed for mixing wine and water. The vessels were made of ceramics or metals, such as bronze, gold, and silver. Typical dimensionless geometrical properties for these four typologies of vessels have been estimated numerically by modeling the vessels using a commercial CAD program [14]. These are:

- the geometrical ratio, $\lambda=h/b$
- the inertial ratio, $\gamma=I_0/mh^2$
- the centroid ratio, $\beta=h/H$
- the volumetric ratio, $v=V/H^3$

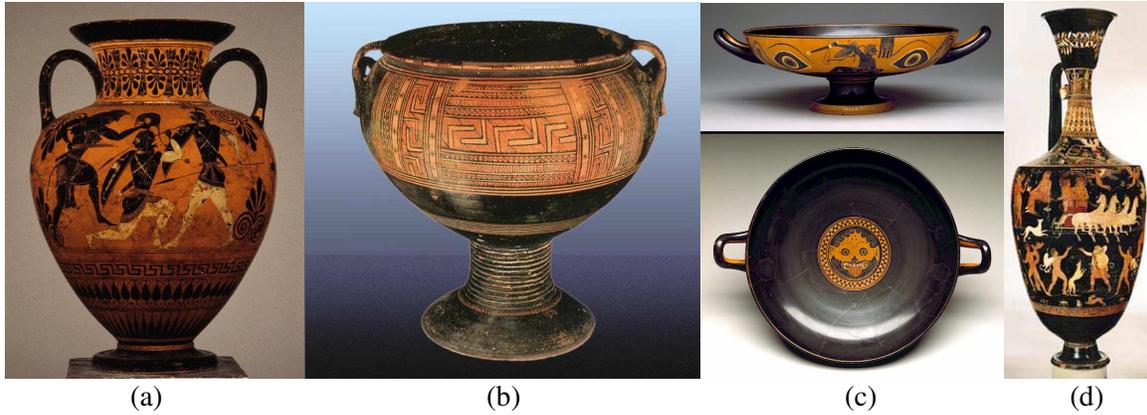


Figure 5. Examples of ancient Greek vessels: (a) amphora, (b) krater, (c) kylix, (d) lekythos.

where H is the total height of the vessel, h is the height of the centroid, b is the half-base, m is the mass, and V is the volume. It is worth to notice that these dimensionless properties, summarized in table 1, are associated only to the shape of the considered vessels and are independent on the vessel size. The dynamics of each object is governed only by three parameters, namely the geometrical ratio λ , the inertial ratio γ and the height of the centre of mass of the object that identifies the scale size. The relevant effect of the scale of the object on its dynamic behavior will be specially investigated.

The first numerical investigation is relative to the behaviors of the considered four vessels subjected to the Athens ground motion. In order to provide a simple measure of the vulnerability of the considered objects, the earthquake record has been scaled to different levels of peak ground acceleration. The results have been reported in the form of behavior maps that summarize the qualitative response of the considered art objects. Figures 6 report the results of extensive numerical investigations relative to the four considered vessels, characterized by the corresponding geometrical ratio λ and inertia ratio γ . The marks in the figures correspond to different heights of the vessel and to different values of the scaled peak ground acceleration. The horizontal green line indicates the actual peak ground acceleration of the considered ground motion.

Table 1. Dimensionless geometrical characteristics of Greek vessels.

Parameter	Typology				
		<i>Amphora</i>	<i>Volute krater</i>	<i>Kylix</i>	<i>Lekythos</i>
Geometric ratio, $\lambda=h/b$		3.8	3.4	1.4	5.3
Inertial ratio, $\gamma=I_0/mh^2$		0.40	0.42	0.83	0.34
Centroid ratio, $\beta=h/H$		0.50	0.59	0.56	0.48
Volumetric ratio, $\nu=V/H^3 (\times 10^{-2})$		1.54	2.47	4.40	0.78

In the maps the empty circles identify situations in which the vessel remains in full contact with the base. In this case it should be verified if the inertial forces in the vessel do not cause damage due to excessive stress. The full circles are relative to cases in which the vessel rocks during the earthquake without overturning. Also in this case, in order to correctly evaluate the vulnerability of the vessel, a verification of the potential damage during the repeated impacts should be performed; this is however beyond the scope of the present investigation. Finally, the full triangles identify situations of potential severe damage because they are associated with the overturning of the object, corresponding to very high impact energy. From the above considerations and from the observation of the behavior maps, it can be concluded that the more vulnerable vessel typology is the lekythos. In fact this kind of vessels tilts up at a very low peak ground acceleration, equal to $0.2g$, and presents a very large instability domain within the investigated region. The more stable typology, with reference to the considered loading, is the kylix that, within the investigated region, never overturns and begins to rock at a high level of peak ground acceleration. This is because its geometrical ratio is 1.4 , therefore the minimum peak ground acceleration that causes the rocking of the object is equal to $1.4^{-1}g = 0.71g$. The other two classes of vessels, the amphora and the volute krater, both exhibit a similar behavior. The first vessel begin to rock for a peak ground acceleration about equal to $0.3g$ and exhibit an unstable behavior for PGA greater than $0.4g$. The second vessel rocks for PGA about equal to $0.35g$ and overturns for the Athens ground motion scaled to $0.45g$.

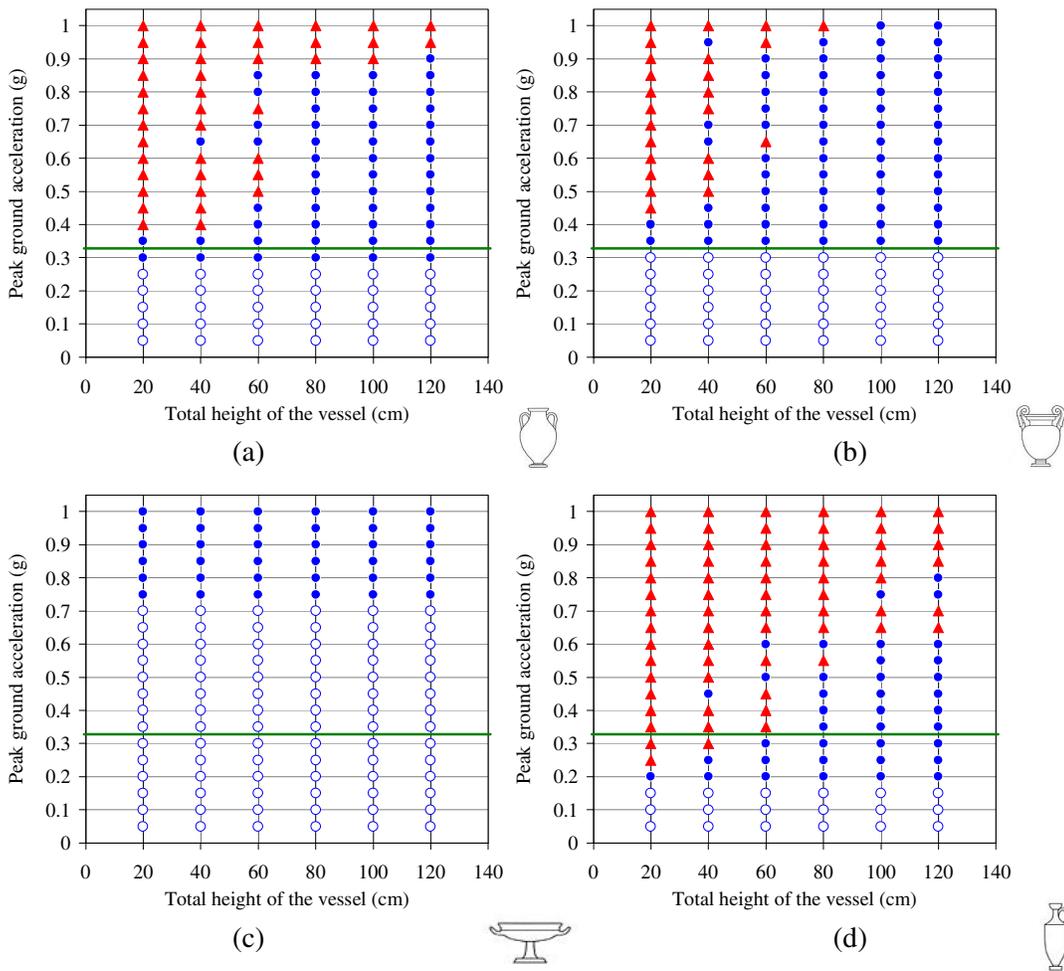


Figure 6. Behavior maps for the Athens ground motion; (a) amphora, (b) volute krater, (c) kylix, (d) lekythos; ○ Full contact, ● Rocking, ▲ overturning.

From the observation of the figures it can be noticed that for each vessel there is a value of the peak ground acceleration, that is independent on the height of the vessel, below which the object maintains the full contact with the base. This fact is well known [1] because the incipient rocking condition depends only on the geometrical ratio λ and on the peak ground acceleration. Moreover, in some maps the strong influence of the scale effect on the stability of the block can be recognized; this effect has been also observed for deformable bodies subjected to uplift [12].

Figures 7 report the results of the dynamic behavior of the considered vessels under the El Centro ground motion. It is of interest to observe that the kylix vessel still exhibits a stable behavior, also with reference to the region in which the object is subjected to uplift, on the contrary the other three typologies of vessels show a high vulnerability to the El Centro ground motion and for the all investigated case generally the phase of rocking is followed by the overturning of the object.

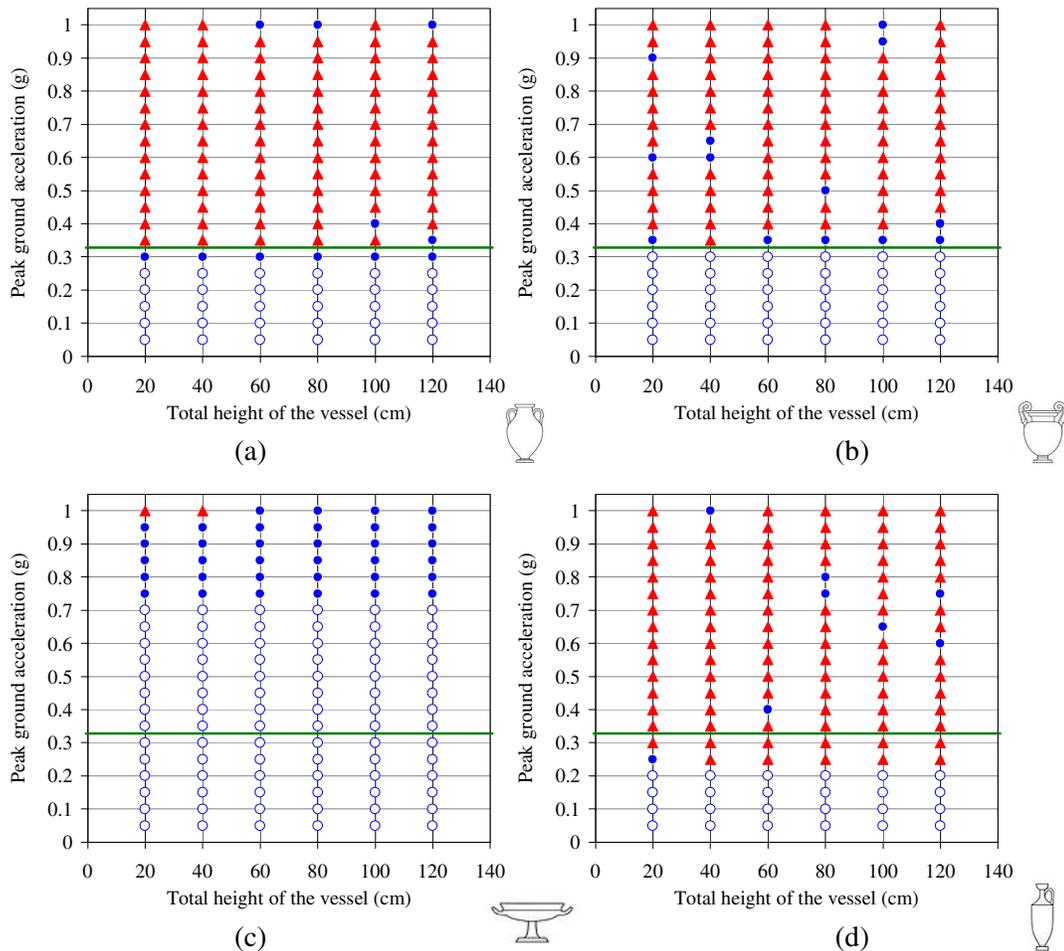


Figure 7. Behavior maps for the El Centro ground motion; (a) amphora, (b) volute krater, (c) kylix, (d) lekythos; \circ Full contact, \bullet Rocking, \blacktriangle overturning.

Statues of human figures

As case-studies of statues representing a human figure, the *kouros of Aristodikos*, which is exhibited in the National Archaeological Museum of Athens, has been considered. The statue is a funerary kouros which represents a deceased whose name, as recorded by the inscription on the base, was Aristodikos. The statue was found in the area of Mesogeia, in Attica and is dated to ca. 500 B.C. The statue, represented in figure 8, is quite symmetrical and represents a human figure 1.98 metres tall above a pedestal of

dimensions $0.30 \times 0.60 \times 0.60 \text{ m}^3$. The mass of the human figure can be estimated in 260 kg, while the mass of the pedestal is about 280 kg, so that the total mass of the object of art is 540 kg. The centre of mass of the statue can be located roughly at 120 cm above the top of the pedestal. The dimensionless geometrical characteristics of the human figure, with and without pedestal, are summarized in table 2.

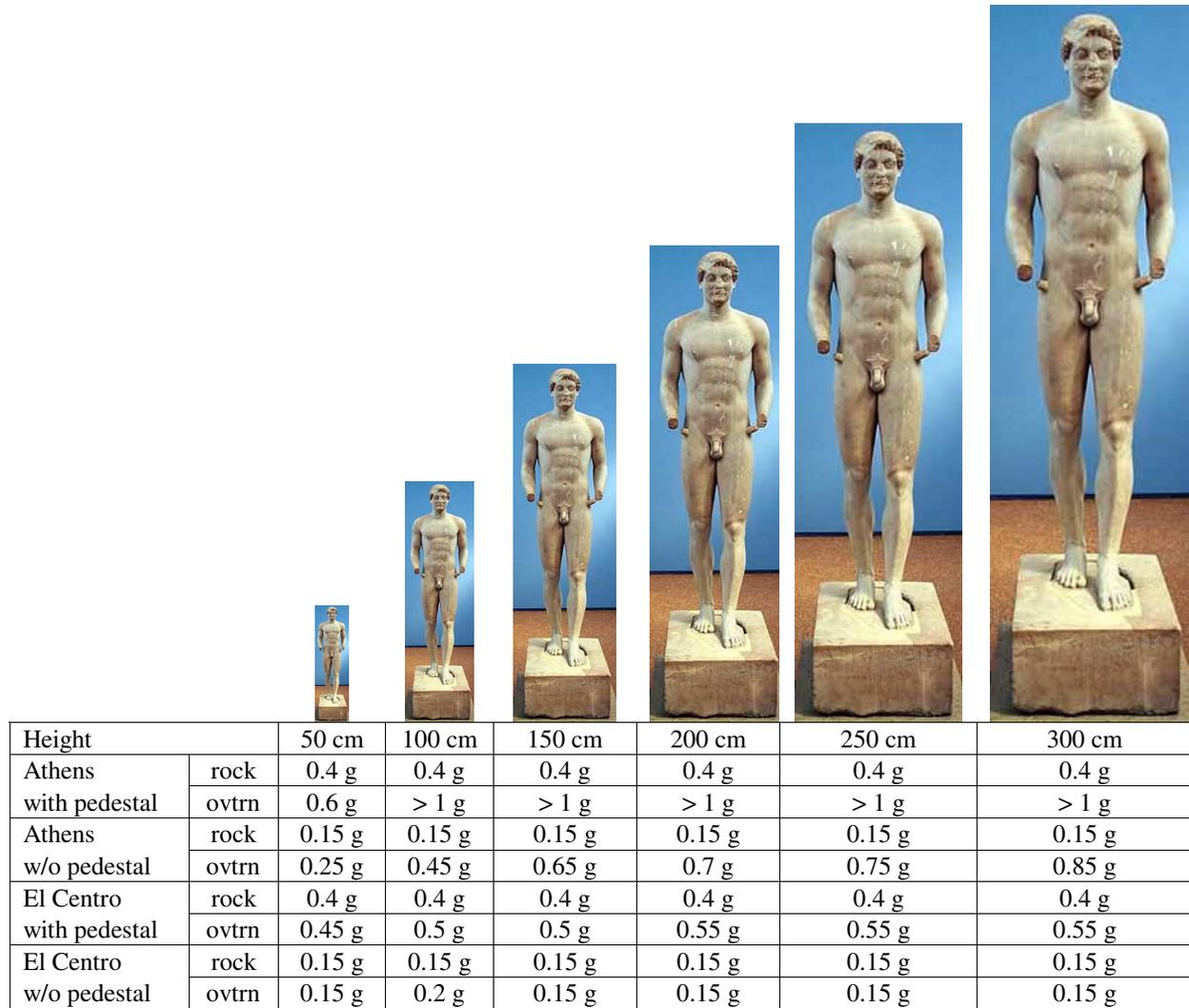


Figure 8. The *kouros of Aristodikos* at various scales.

To the aim to give indications for similar statues but different sizes, the analyses will be performed for different height of centre of mass. In order to emphasize the importance of the scale effect, in the figure 8 the statue of the kouros of Aristidikos is repeated many times maintaining the scale differences considered in the analyses. Below each figure the corresponding minimum PGA that causes the rocking as well as the minimum PGA that causes the overturning, with reference to the considered ground motions, are reported. Furthermore, in order to evaluate the beneficial effect of pedestal (that, reducing the height of mass centre, determines a significant reduction of the geometrical ratio), the analyses have been performed considering the statue with and without the pedestal. The results, reported in figures 9 and 10, are presented in the same form as those concerning the Greek vessels.

Table 2. Dimensionless geometrical characteristics of the kouros of Aristodikos (National Archaeological Museum of Athens).

	Without pedestal	With pedestal
Geometric ratio, $\lambda=h/b$	8.0	2.7
Inertia ratio, $\gamma=I_0/mh^2$	0.30	0.3
Centroid ratio, $\beta=h/H$	0.61	0.35
Volumetric ratio, $v=V/H^3 (\times 10^{-2})$	1.29	1.75

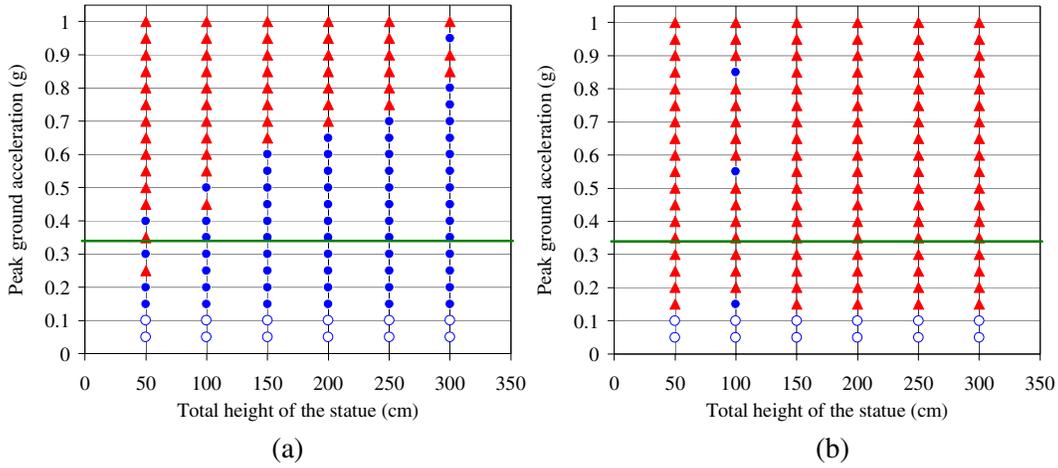


Figure 9. Behavior maps for statues of a human figure without pedestal subjected to earthquake loading: (a) Athens ground motion, (b) El Centro ground motion.

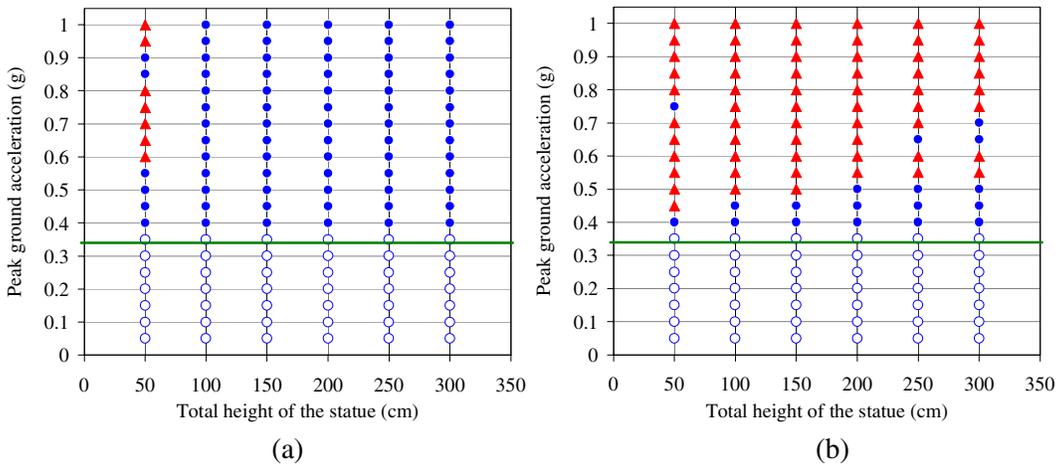


Figure 10. Behavior maps for statues of a human figure with pedestal subjected to earthquake loading: (a) Athens ground motion, (b) El Centro ground motion.

The comparison between the obtained results, relative to both the ground motions considered, shows that the behavior maps relative to the El Centro ground motion are characterized by a very large unstable region, while the maps relative to the Athens ground motion present wide regions characterized by rocking without overturning. Furthermore it can be observed the beneficial effect of the pedestal that strongly reduces the vulnerability of the statue increasing the minimum PGA that causes the rocking of the statue.

MITIGATION OF THE SEISMIC RISK OF ART OBJECTS VIA BASE-ISOLATION

In a previous work [9] the present authors introduced a non-linear plane model for the evaluation of the effect of the seismic isolation for the art objects. The model, shown in figure 11, consists of a symmetric rigid block, which represents the object of art, simply supported on a movable horizontal support of mass m_s . The movable mass may displace horizontally and is restrained to a fixed support by means of a linear elastic spring with stiffness k and a viscous damper of constant c . The upheld object has mass m and rotational inertia about its centre of mass I_o and is able to rock over the movable support, while the sliding is prevented by means of seismic constraints or by the friction. The height of the mass centre of the object is equal to h , b is its half base and r is the distance between one corner of its base and the mass centre.

The dynamic response of this model can exhibit two different phases of motion. In the phase of *rocking* the system has two degrees of freedom, one relative to the motion of the support and the other corresponding to the rotation of the object about one of its ends. In the *full-contact* phase, when the object moves together with the support, the system is linear and exhibits a single degree of freedom. The non-linear equations of motion as well as the transition conditions are reported in the quoted paper. This model has been used to verify the efficiency and to evaluate the performance of base-isolation systems for the previously considered art objects.

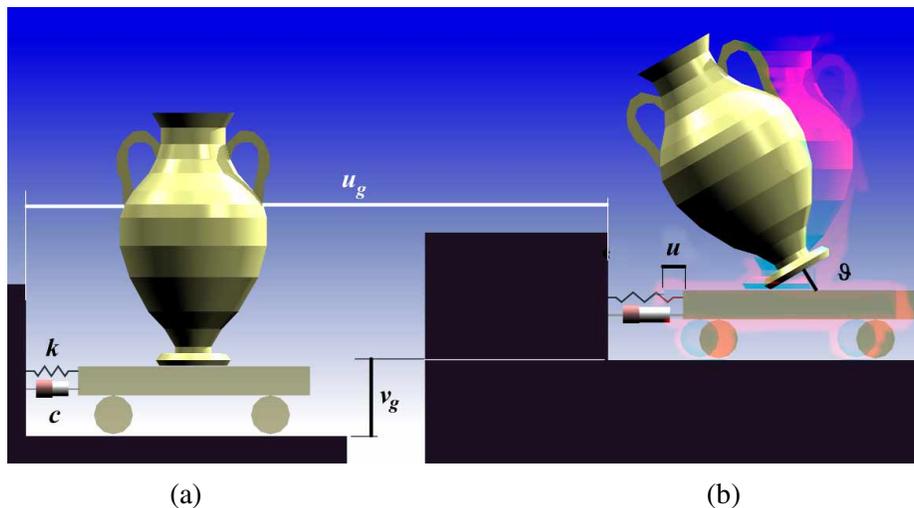


Figure 11. (a) The considered model; (b) the kinematics.

Greek vessels

The results reported in figures 12a and 13b are relative to the more vulnerable of among the considered vessels, the lekythos, upheld on a base isolated support and subjected to the Athens ground motion. In the figures the seismic behaviour of the vessel simply supported on a particular base-isolated support are summarized considering the same representation used for the non-isolated vessels reported in figures 6 and 7. Figure 12a is relative to a Lekythos on a base isolated system characterised by a period on a fixed base equal to $T = 1$ s, a damping ratio $\xi = 15\%$ and mass ratio $m_s/m = 100$; figure 12b differs only for the value of the fixed base period that is equal to $T = 1.5$ s. The same results, but with reference to the El Centro ground motion, are reported in figure 13. From the observation of the figures it can be noticed a significant increment of the values of PGA that cause the rocking and the overturning of the object. The isolation effect increases as the period of the system on a fixed base increases; however the augmentation of the period produces a growth of the maximum displacement of the support. The effect of the period of

the base-isolation system on the minimum PGAs that produce the rocking and the overturning of the object has been investigated and the results are reported in figure 14a, with reference to Athens ground motion, and in figure 14b, for El Centro ground motion. It is important to observe that, although the considered earthquakes are characterised by the same value of PGA, the El Centro ground motion is more severe also for the base-isolated systems.

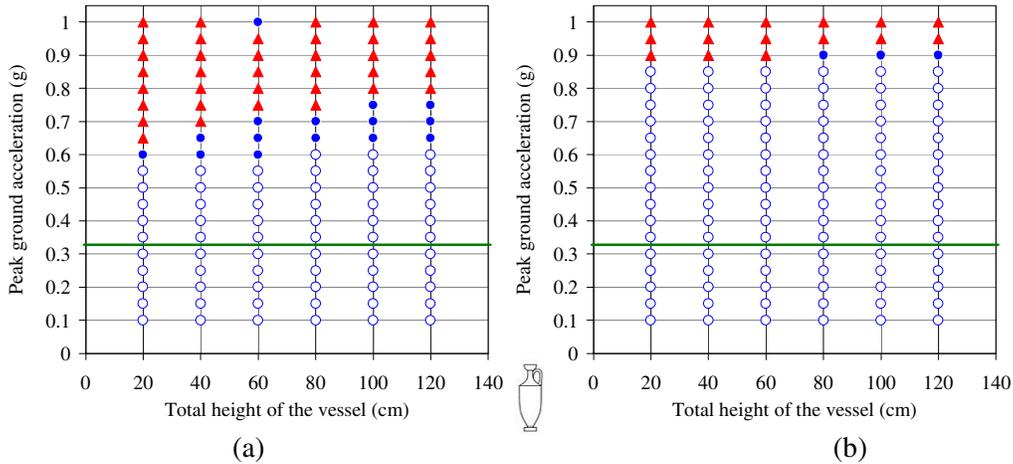


Figure 12. Behavior maps for base-isolated Lekythos vessels subjected to the Athens ground motion: \circ Full contact, \bullet Rocking, \blacktriangle overturning.
 (a) $T=1$ s, $\zeta=15\%$, $m_s/m=100$. (b) $T=1.5$ s, $\zeta=15\%$, $m_s/m=100$.

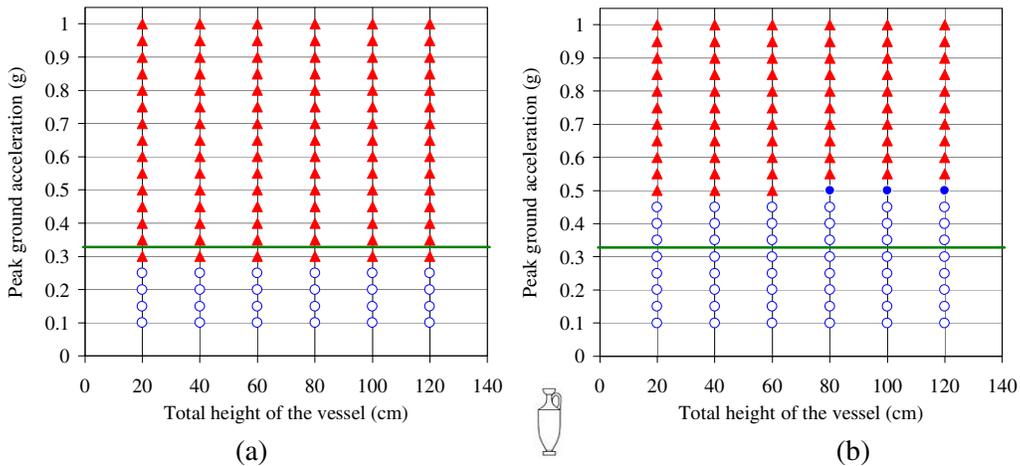


Figure 13. Behavior maps for base-isolated Lekythos vessels subjected to the El Centro ground motion: \circ Full contact, \bullet Rocking, \blacktriangle overturning.
 (a) $T=1$ s, $\zeta=15\%$, $m_s/m=100$. (b) $T=1.5$ s, $\zeta=15\%$, $m_s/m=100$.

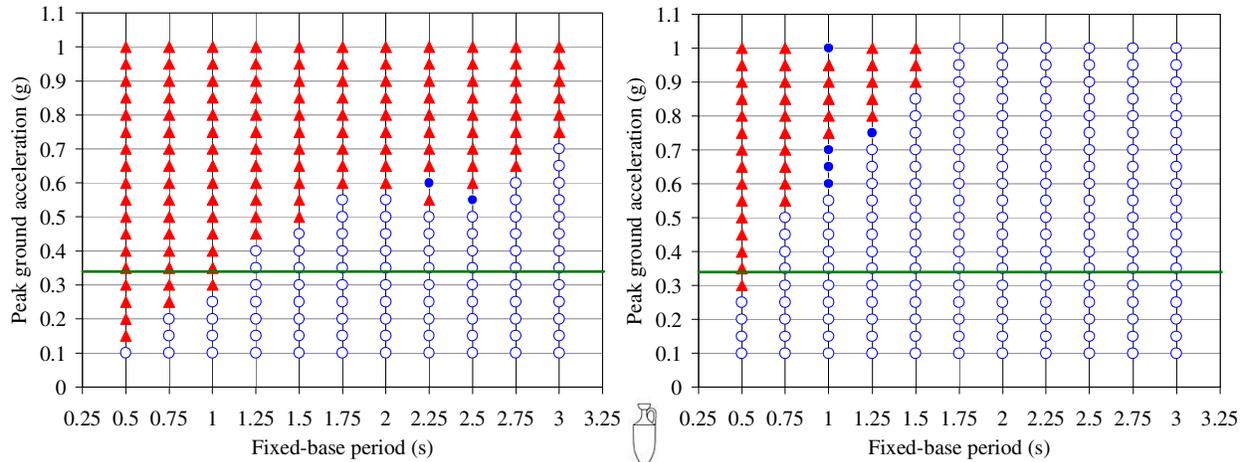


Figure 14. Behavior maps for a base-isolated Lekythos vessel subjected to earthquake loading; $H=60$ cm, $\zeta=15\%$, $m_s/m=100$; \circ Full contact, \bullet Rocking, \blacktriangle overturning.
 (a) Athens ground motion. (b) El Centro ground motion.

Statues of human figures

In the following figures the behavior maps for the statues analyzed in the previous paragraphs (figures 9 and 10) when a base isolation system is applied are reported. The considered seismic isolation system is characterized by a fixed base period $T=2$ s, a damping ratio $\zeta=15\%$ and a mass ratio $m_s/m=6$. By the observation of the results a strongly different behavior for the two ground motion considered emerges. In fact, with reference to the Athens ground motion, the object simply supported on the seismic isolation system does not rock even if the ground motion is scaled to 1g; on the contrary, with reference to El Centro ground motion, the presence of isolation system determines a seismic risk mitigation, but the object remains still vulnerable for values of PGA larger than 0.4g.

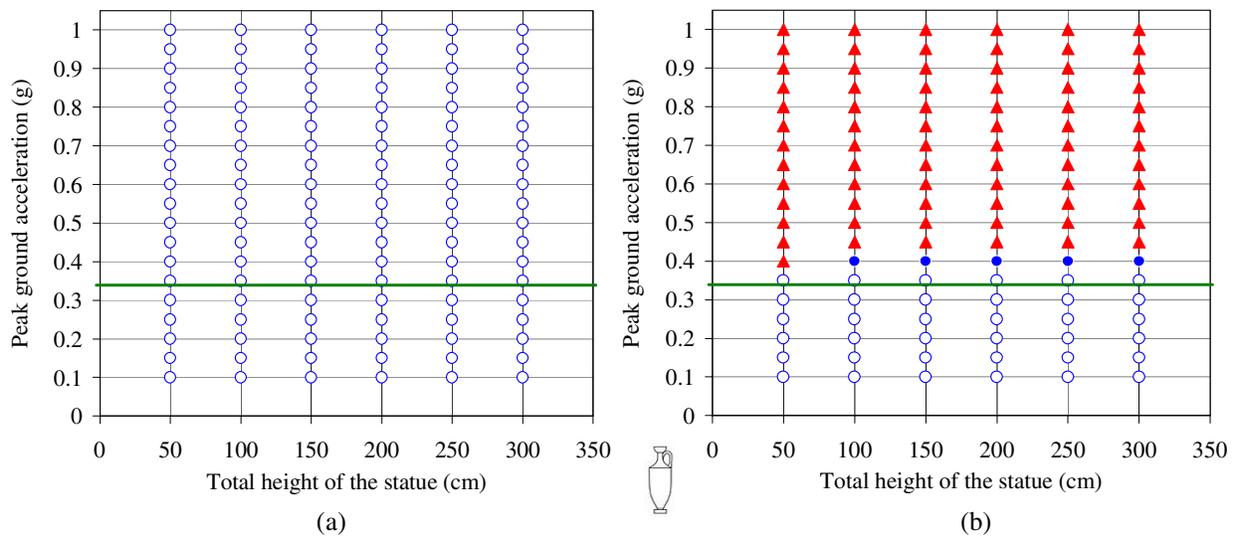


Figure 15. Behavior maps for base-isolated statues of a human figure subjected to earthquake loading; \circ Full contact, \bullet Rocking, \blacktriangle overturning; $T=2$ s, $\zeta=15\%$, $m_s/m=6$.
 (a) Athens ground motion, (b) El Centro ground motion.

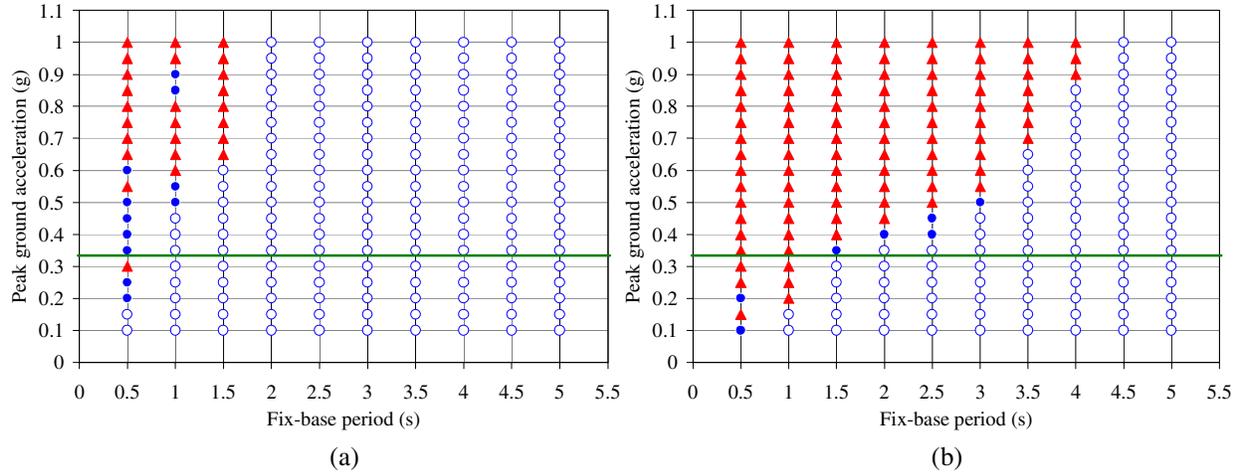


Figure 16. Behavior maps for base-isolated statues of a human figure subjected to earthquake loading; Full contact, ● Rocking, ▲ overturning; $H=200$ cm, $\zeta=15\%$, $m_s/m=6$.
 (a) Athens ground motion, (b) El Centro ground motion.

In order to better investigate the role of the period of the isolation system, the results of numerical analyses for the statue of the kouros of Aristodikos without the pedestal subjected to the considered scaled ground motions for different values of the fixed base period of the isolation system are summarized in figures 16. The results clearly show that, in order to obtain a satisfactory mitigation of the seismic risk, it is important to realize an isolation support characterized by a very long period. However, as have been said before, this requirement cannot be easily met for two practical constraints. The first problem is associated to the large displacement of the support which is produced by a very long period isolation, the second and more stringent condition is related to the manufacturing of such devices.

CONCLUSIONS

The past and the recent seismic events clearly showed the high vulnerability of art objects and of museum contents also for moderate earthquakes. However, in the studies relative to the prevention of seismic damage, a marginal attention has been paid, so far, to the problems related to the safeguard of art objects that, in most cases, have an inestimable value and represent a common heritage that must be protected. From a structural point of view, the seismic behavior of art objects in many cases can be analyzed within the context of the dynamic response of rigid blocks under seismic loads. In the paper the seismic vulnerability of some classes of art objects, with and without a seismic isolation as a measure for the mitigation of the seismic risk, has been investigated. Namely the seismic behaviors of ancient Greek vessels as well as of stone statues have been analyzed with reference to different seismic loadings. The art object has been considered as a rigid block simply supported on a rigid base with sliding prevented. The applications have been performed for large displacements kinematics but considering only the rocking behavior of the object according to the *simple rocking model* [11]. The results of extensive numerical investigations show the high vulnerability of arts objects subjected to earthquake excitations, especially in the case of small objects due to the well known influence of the scale effect for the rigid block. The beneficial effect of the seismic isolation as a safeguard measure has been analyzed. The obtained results clearly show that it is important to realize isolation supports characterized by very long period in order to obtain satisfactory results. In many cases the risk is increased by the fact that the seismic acceleration is significantly amplified by the structure in which the object is exposed or kept; this particular aspect is under investigation and will be presented in a paper to come.

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