A new approach for the Seismic Isolation Methods for Ancient Statues Displayed in Base Isolated Museums

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SUMMARY:
In order to protect the precious art and historical objects on display, recently the museum buildings in earthquake prone countries are designed and constructed with seismic base isolation devices, at the foundation level. However, when adopting conventional base isolation devices (e.g. LRB, friction pendulum), the horizontal accelerations in the building can be significantly reduced, while the vertical accelerations are directly transmitted to the building's contents. If these vertical accelerations reach significant values, the stability of the objects decreases against overturning, and this causes the object to lose its full contact with the ground and to start rocking. Therefore, to protect the contents of a base isolated museum building against three directional earthquake excitations, a vertical seismic isolation solution must also be introduced at the base level of the object. This study aims to assess the performance of vertical isolation devices for the seismic protection of the ancient statues displayed in base isolated museums.

Keywords: Vertical isolation, ancient statues, initiation of rocking

1. INTRODUCTION

The horizontal accelerations, transmitted to the statues displayed in a museum building, can be reduced satisfactorily by adopting seismic isolation devices at the foundation level of the building. However, since isolating a building in the vertical direction is not practical because of its large static weight, the vertical component of the earthquake is usually directly transmitted to its contents also in the case of buildings base isolated by means of conventional isolation devices. Strong vertical accelerations, if directed upwards, may considerably reduce the gravity's stabilizing effect, so that an object can easily lose its contact with the ground, and starts rocking. During the rocking motion, the object gets impacts while rotating from one of its corners to the other, hence it is given an energy input, which must be dissipated in such a way, not to cause damage to the artifact. Due to the vulnerable structure of ancient statues, which are often made of brittle material and already have cracks and damages due to the previous hazards experienced in their life time, this energy input through such impacts, can cause irrecoverable damage, and sometimes even loss of priceless cultural heritage of human history. Since a plastic behavior cannot be expected from the brittle structure of an ancient statue, this input energy can be only dissipated with an effective seismic isolation solution taking into account the multi-directional nature of the earthquake excitations.

2. VERTICAL SEISMIC ISOLATION SYSTEM

In a base isolated museum building, placing the statues upon an additional local horizontal isolation system does not help reducing the accelerations, in the contrary, since the frequency contents of the building and the isolated platform of statues might become similar to each other, the seismic risk for the statues increase, because of a possible resonance problem. Therefore in order to achieve an effective three directional isolation system in a base isolated museum building, the rigid platform on which the statues are placed is restrained to the ground horizontally, and vertical seismic isolators are mounted between the statue and the rigid platform (figure 1).

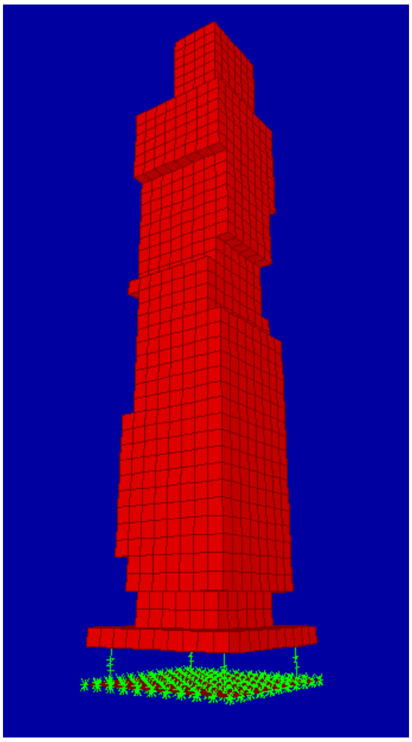

Figure 1 Vertical Isolation Model

The vertical isolation system consists of four springs with linear spring constant k and damping coefficient c. In the computer model, to simulate a vertical base isolation device, a gap ("compression only") element is used (figure 2). The force deformation relationship of this element is given by Eqn.1.

$$f(x) = \begin{cases} k(d + open)......if : d + open < 0 \\ 0,..........otherwise \end{cases} \tag{1}$$

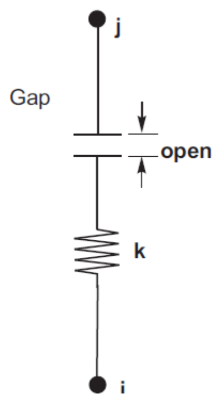

Figure 2 Vertical isolator element

As it can be seen in figure 3, the gap elements have a linear behavior under compression, and they cannot carry any tensile load. In other words, they provide linear stiffness only under compressive loads. In the model, thanks to the self weight of the statues, these elements are initially compressed. Therefore during the vertical earthquake excitations, they are expected to take action only in the compression range. The vertical isolator elements are constrained at the vertical (z) axis in order to avoid differential displacements.

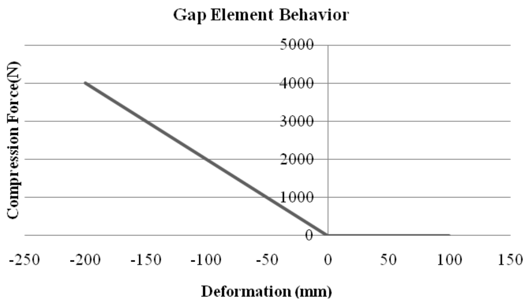

Figure 3 Gap element behaviour

The numerical analyses are carried out in three stages. First, the acceleration time-history data of the earthquakes are applied to a three-storey reinforced concrete frame that could represent a generic museum building with a horizontal base isolation system. Then, the acceleration time-history data are obtained at each floor of the building model. Finally, the acceleration time-history data obtained from this model are given as the time history acceleration input to the ancient statue model. The general scheme of the analyses can be observed in figure 4. Several analyses are carried out under different seismic excitation data in order to verify the efficiency of the vertical isolation elements on the reduction of vertical accelerations measured on the artifacts. Consequently, for the same statue model, rocking evaluation is done under the maximum accelerations obtained in the analyses.

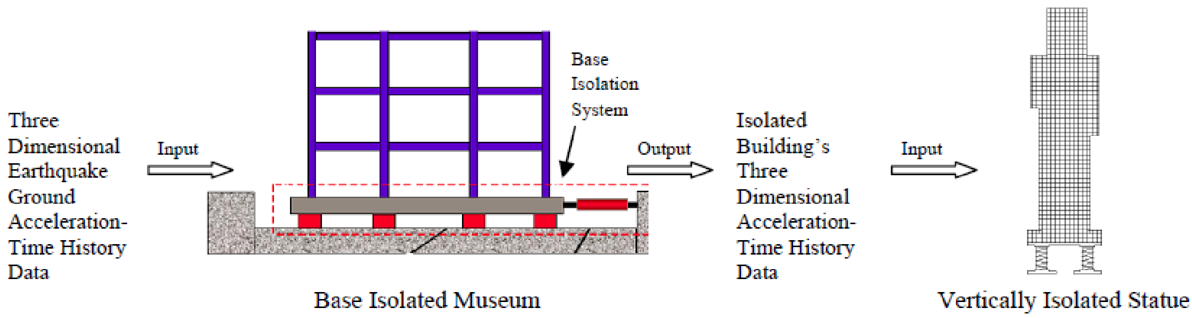

Figure 4 The general scheme of analysis

For each statue, four vertical seismic isolator elements are used with linear stiffness values of 20 N/mm. From table 1, the amount of reduced accelerations and the percentage of reductions in each direction can be seen. Note that in this table, the reductions in the horizontal accelerations are obtained thanks to the horizontal base isolation of the building.

Table 1 Reductions in accelerations for the vertically isolated statues placed in the base isolated museum building

Vertically Isolated Statue Placed in a Base Isolated Building	Longitudinal Maximum Acceleration (g)	Translational Maximum Acceleration (g)	Vertical Maximum Acceleration (g)
Athens 1999	0,17g	0,19g	0,24g
reduced by:	80%	81%	80%
El Centro 1940	0,17g	0,13g	0,05g
reduced by:	46%	41%	75%
Aquila 2009	0,08g	0,04g	0,09g
reduced by:	81%	91%	82%

Using four vertical isolator springs with the stiffness of 20 N/mm under the base of the statue, the initial vertical displacement under the self weight of the statue is 17.8 cm, whereas, it reaches up to 21.65 cm under the strongest vertical excitation (Athens 1999 Earthquake) These results show that under three earthquake excitations, the linear vertical isolator elements perform effectively, satisfying the two necessary requirements:

-They are always under compression
-Their vertical displacement values are within the limits that available products in the market can provide.

From figure 5 to 7, link-deformation graphs of the vertical isolator elements, obtained under three different earthquake ground motion can be seen.

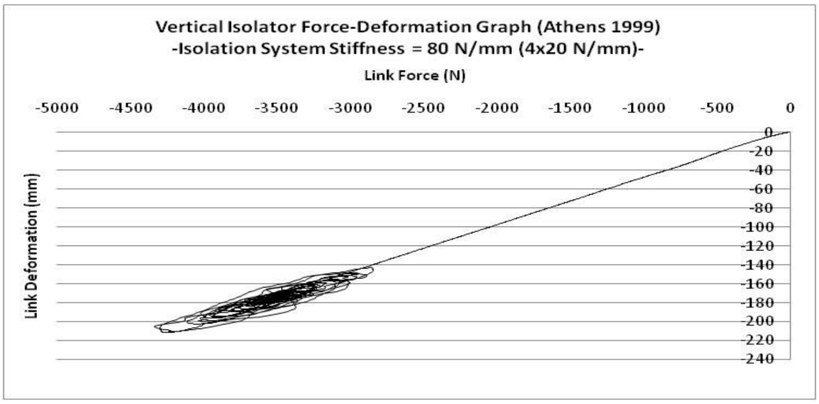

Figure 5 Vertical isolator force-deformation graph, Athens 1999 Earthquake

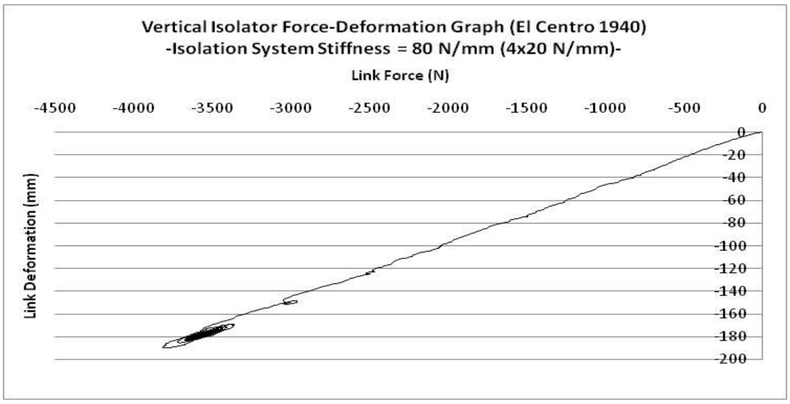

Figure 6 Vertical isolator force-deformation graph, El Centro 1940 Earthquake

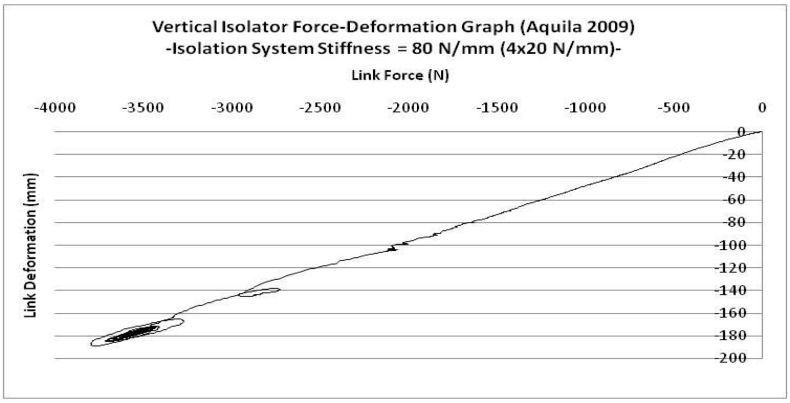

Figure 7 Vertical isolator force-deformation graph, Aquila 2009 Earthquake

2. ROCKING ANALYIS

If the vibrations are exceeded above a certain limit, the rigid blocks start "rocking". Statically, when the overturning moment caused by earthquake forces reaches the resisting moment due to the self weight, the object starts to rock. This condition in the hypothesis of horizontally restrained displacements and of vertical unilateral restraint (compression only) at the base of the statue, can be demonstrated with the Eqn.2 and Eqn.3 for a statue shown in figure 8

$$M_{overturning} = M_{resisting} \tag{2}$$

$$h(ma_h) = b(mg \pm ma_v) \tag{3}$$

where,
h = Height of the center of mass of the object
b = Lateral distance between the overturning point and the center of mass of the object
m = Mass of the object
g = Gravity acceleration
a_h = Horizontal acceleration
a_v = Vertical acceleration

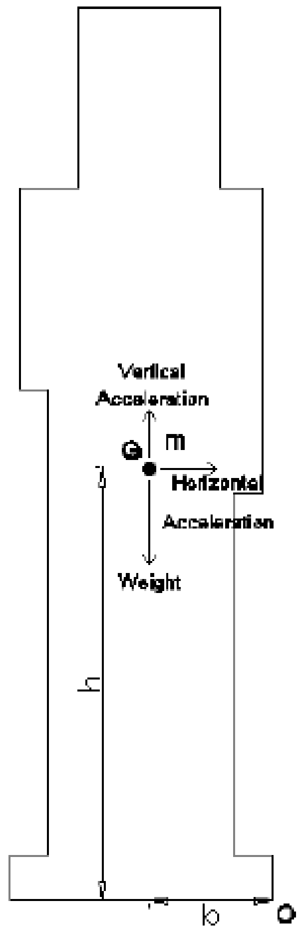

Figure 8 Ancient statue rigid body model

However, since earthquake forces are impulsive, the static approach may not give satisfying results.. Therefore, the accelerations that can start the rocking of a rigid body is estimated using an "impulsive loading approach", in which the minimum impulse that a specific rigid block can tolerate named as "overturning impulse" is compared with the impulse caused by the maximum accelerations of the earthquake excitations.

A rigid block, subjected to the horizontal and vertical accelerations, can either remain in full contact with the ground or it uplifts and starts rocking. During this motion, if the acceleration impulse caused by the earthquake forces becomes larger than the minimum "overturning impulse" of the system, the object overturns. Otherwise, it continues rocking until the ground motion comes to the end (figure 9). The object's full contact to the ground can be kept, if the magnitude of the impulse remains smaller than the minimum impulse required for uplift for the object (Oliveto et. al. 2002).
While adopting an isolation solution for the protection of ancient statues, attention must be paid to the initiation of uplift because, once the object begins rocking, it starts to have impacts while rotating from one of its corners to the other, and this action may cause serious damage. In this study, assessment of the horizontal and vertical accelerations that allow the statue to remain in full contact with the ground is carried out in presence of suitable vertical isolation elements.

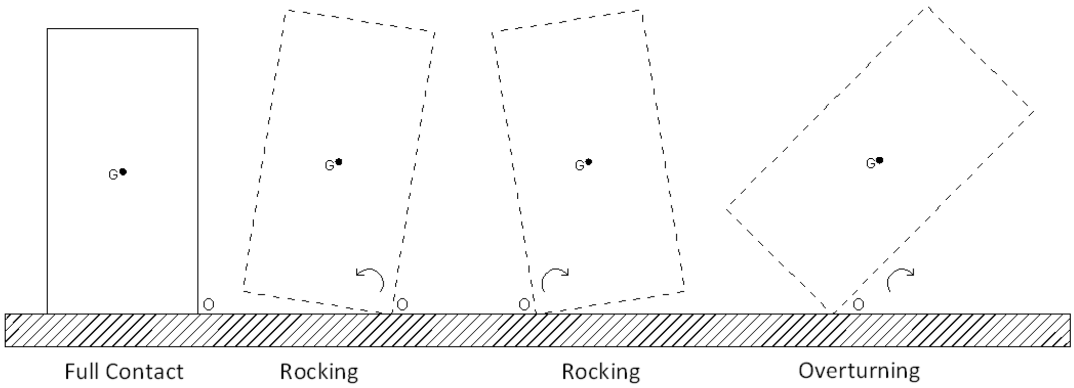

Figure 9 Rocking and overturning

The minimum impulse that initiates the rocking motion of an object is called as the minimum uplift impulse (Oliveto et. al. 2002). It depends on the object's geometric properties (slenderness), natural frequency, (stiffness and mass), and the vertical ground motions. Comparing the minimum uplift impulse of a particular object with the impulse caused by the maximum expected earthquake accelerations (named as "design impulse"), the probability for the initiation of rocking can be foreseen. Finally, interaction diagrams between horizontal and vertical accelerations for the specific ground motions can be derived. Examining these diagrams, the allowable horizontal and vertical accelerations that can keep the statue model in full contact with the ground can be decided.
The minimum uplift impulse that causes rocking of an object has been expressed by Calio and Marletta (2003). The minimum rocking impulse Iu, has been derived by equating the overturning moment due to the inertia load caused by the maximum horizontal acceleration, to the resisting moment due to the gravity as shown in Eqn.4;

$$\ddot{u}_{\max}(I_r) = \frac{gb}{h} = \frac{g}{\lambda} \tag{4}$$

Considering zero damping, the maximum acceleration is given by Eqn.5

$$\ddot{u}_{\max} = I\omega \tag{5}$$

Therefore the minimum impulse that starts the rocking motion of a rigid body is represented in Eqn.6

$$I_u = \frac{g}{\omega\lambda} = \frac{g}{2\pi\lambda}T \tag{6}$$

Where,

g = gravity acceleration
h = height of the center of mass of the object
b = lateral distance between the overturning point and the center of mass

λ= h/b (slenderness ratio)
ω= natural frequency of the object
T = natural period

Calio and Marletta (2003) concluded that the object stays in full contact with the ground until the design impulse becomes equal to the minimum uplift impulse. When the minimum uplift impulse is surpassed, the object starts rocking. The same author has shown that the seismic isolation significantly contributes to the stability of the object under horizontal ground motions.

Oliveto et. al (2002) evaluated the uplift conditions for the initiation of rocking motion, considering both horizontal and vertical ground motions. They introduced a dimensionless parameter γ, to take into account the vertical accelerations of the ground motion (Eqn.7).

$$\gamma = 1 + \frac{\ddot{v}_g}{g} \tag{7}$$

Where

$\ddot{v}_g$ = Vertical ground acceleration (positive, when directed downwards)
g = Gravity acceleration (m/s^2)

They pointed out the significance of the vertical accelerations on the minimum uplift impulse, and expressed it through modifying the minimum uplift impulse expression (Eqn.8)

$$I_u = \frac{\gamma g}{\omega \lambda} = \frac{\gamma g}{2\pi\lambda} T \tag{8}$$

In the absence of damping, the minimum uplift impulse of a structure can be found according to equation (5), which shows that, the minimum uplift impulse decreases with the increasing natural frequency and slenderness. Also, the vertical accelerations have a direct effect on the motion. From the equation (5), it can be concluded that,

- More rigid structures (with higher natural frequency) are easier to uplift, than the flexible ones.
- More slender structures (higher h/b ratio) are easier to uplift than the less slender ones
- The upward vertical accelerations reduce the minimum uplift impulse, which results in a lower resistance to the uplift.

Thus, it can be understood that vertical accelerations of the earthquakes are very important for the uplift resistance of the object. The higher values the vertical accelerations have in the upward direction, the easier is the initiation of the uplift.
For instance, if the maximum vertical accelerations of an earthquake equals to –g, the vertical excitation parameter, γ (see equation 4) becomes zero, so does the minimum uplift impulse, Iu. This practically means “zero” resistance to uplift, therefore in such a case, even a slight horizontal impulse would be enough to start rocking of the object.
Therefore the effect of the magnitude of maximum vertical accelerations to the uplift resistance of the statue is investigated. To estimate the magnitude of the design impulse, the time integral of the earthquake force p(t) should be calculated (Eqn.9, Eqn.10).

$$\text{Earthquake Force: } p(t) = m\,\ddot{u}_h(t) \tag{9}$$

$$\text{Magnitude of Design Impulse: } \int_{t1}^{t2} p(t)dt \tag{10}$$

This integral can be estimated as the multiplication of the mass of the statue and the area under the acceleration time history graph between two successive time instants, corresponding to the maximum horizontal acceleration. As a reasonable estimation, the area of the triangular (Eqn.11) that is drawn in the acceleration time history diagram in figure 10 gives the magnitude of impulse for unit mass.

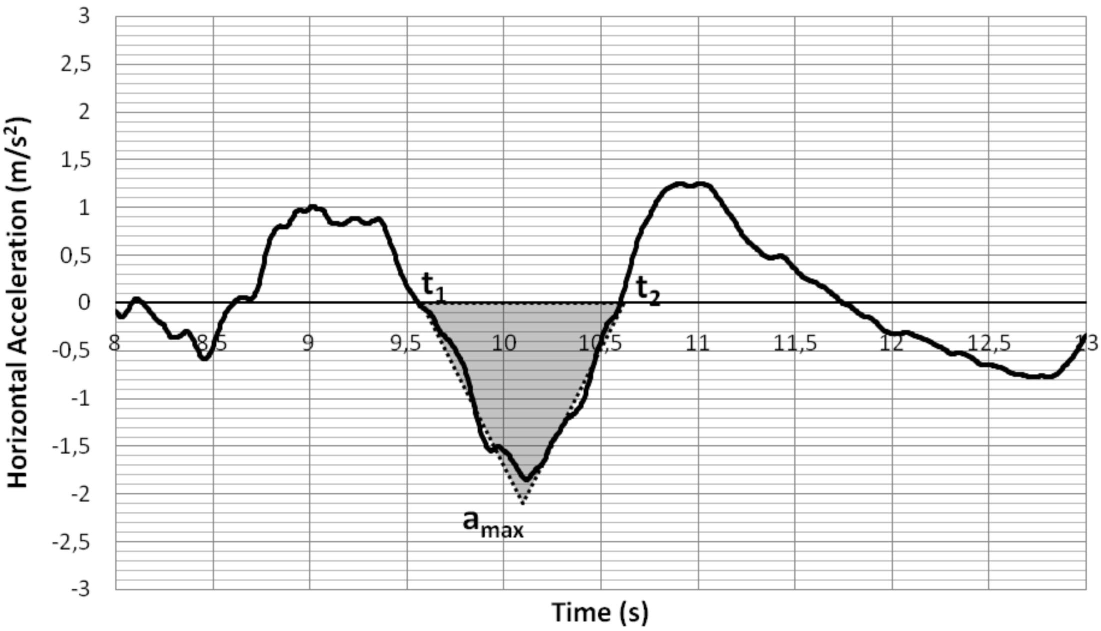

Figure 10 Impulse calculation graph

$$I_d = a_{\max} \cdot \frac{1}{2}(t_2 - t_1) \text{ (for unit mass)} \qquad (11)$$

In the analyses, the comparison between the design impulse and the minimum rocking impulse of the statue is made by considering three different earthquake data, the properties of which are presented in the previous sections.
The comparison between the magnitude of the design impulse and the minimum uplift impulse shows if the object begins to rock or stays in full contact with the ground.
- If the design impulse is smaller than the minimum uplift impulse, the statue stays in full contact with the ground

$$I_d < I_u \rightarrow \text{Full Contact}$$

- If the design impulse is larger than the minimum uplift impulse, the object starts to rocking

$$I_d > I_u \rightarrow \text{Rocking}$$

To generalize the results for all three of the earthquake data, the same calculation procedure is applied with particular parameters of each analyses, and the results are presented as interaction graphs between the horizontal and vertical accelerations. The interaction graphs are shown in the figures 11, 12 and 13. The trend line shows the intersection of the magnitudes of maximum horizontal and vertical accelerations below which the statue stays in full contact with the ground, during the specific earthquake motion. The points above the trend line represent the acceleration values that are sufficient to start the rocking motion.

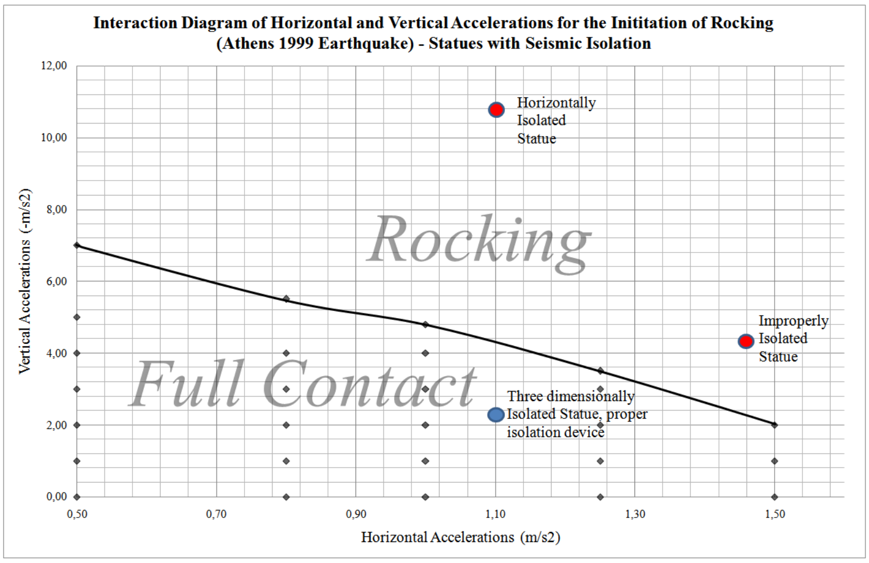

Figure 11 Interaction diagram of horizontal and vertical accelerations for the initiation of rocking

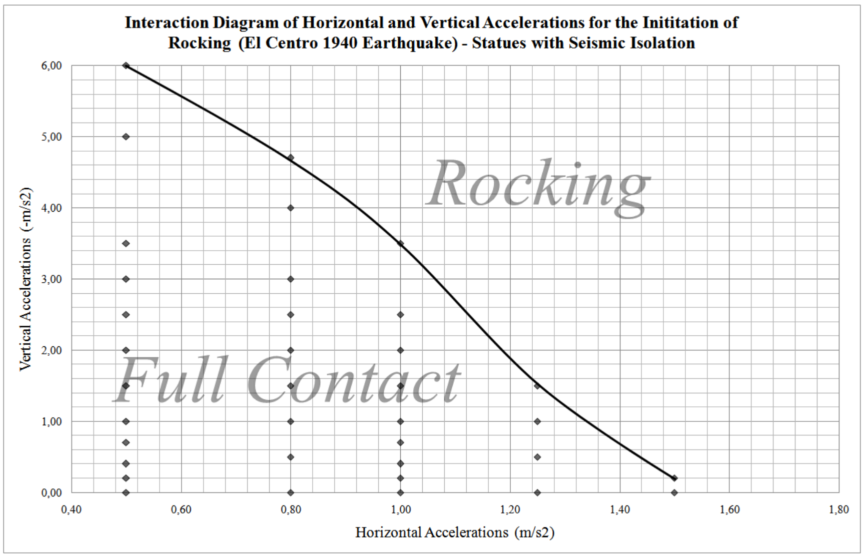

Figure 12 Interaction diagram of horizontal and vertical accelerations for the initiation of rocking

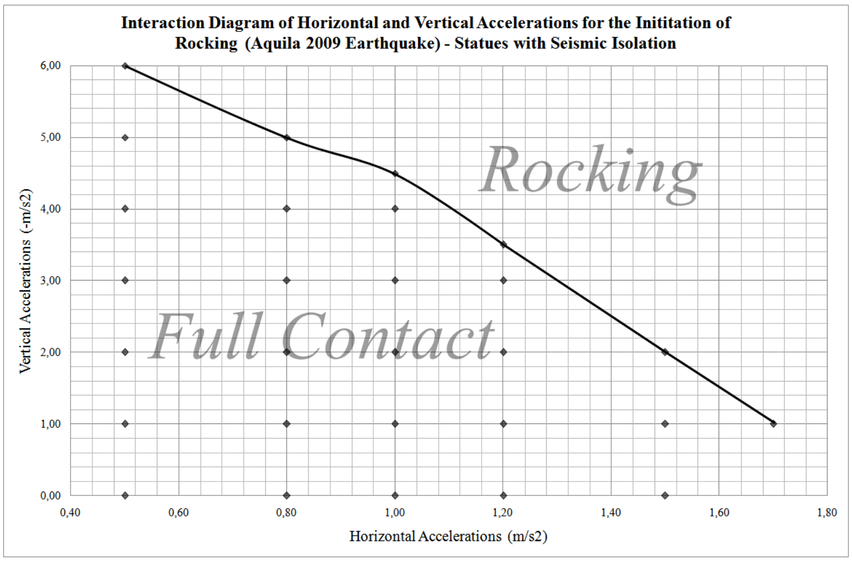

Figure 13 Interaction diagram of horizontal and vertical accelerations for the initiation of rocking

4. CONCLUSIONS

In this study, the effective ways to protect ancient statues against three directional earthquake ground motions are investigated through seismic isolation methods. Several numerical analyses are carried out to understand which type of isolation system is suitable for each case. It is seen that both the horizontal and vertical accelerations transmitted to the statues can be reduced significantly, with a combination of vertical isolators at the base of the statues and horizontal base isolation system of the building. If the museum building in which the statues are to be displayed is not base isolated, then a three directional isolation system must be adopted for the statues.
Rocking analyses are carried out with the results obtained in each case. The results of the rocking calculations for each earthquake data are presented as interaction graphs to show the allowable accelerations under which the statues remain in full contact with the ground, and suffers no damage due to the impacts during rocking. Principally, it is understood that the vertical earthquake excitations play a very important role on the initiation of uplift of the statues.
It is shown that ancient statues can be protected against three dimensional earthquake excitations effectively, when a seismic isolation system is designed according to their particular material and geometrical properties and the characteristics of the building in which they are to be displayed.
This study makes reference to a real case-study, an archaeological museum, base isolated, recently built in an historical European Capital, in earthquake zone. Such museum opened to the public in 2010, hosts one of the largest archaeological collections of the world, among which there are the statues of five "ancient ladies". It is the authors' opinion that these wonderful and very important artifacts are at risk of overturning in case of a strong earthquake.

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