



VERTICAL SEISMIC ISOLATION OF ANCIENT STATUES DISPLAYED IN BASE ISOLATED MUSEUM BUILDINGS

Kubilay KAPTAN¹

¹ Beykent University, Civil Engineering Department, Istanbul, TURKEY
kaptankubilay@gmail.com

Received: 06.05.2015, Accepted: 09.07.2015

*Corresponding author

Abstract

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 dimensional 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, Statues, Initiation of Rocking

TABANI İZOLE MÜZE BİNALARINDA GÖRÜNTÜLENEN ESKİ HEYKELLERİN DİKEY SİSMİK İZOLASYONU

ÖZET

Sergilenen değerli sanat ve tarihi objeleri korumak için, depremsellik yönünden hassas ülkelerde son zamanlarda müze binaları temel seviyesinde sismik taban izolasyon cihazları ile tasarlanmıştır ve inşa edilmiştir. Ancak, geleneksel temel yalıtım cihazları kullanılırken (örneğin LRB, sürtünmeli sarkaç), düşey ivmeler doğrudan binanın içeriğine iletilirken binanın yatay ivmeleri önemli ölçüde azaltılabilir. Eğer bu düşey ivmeler önemli değerlere ulaşırsa, nesnelerin devrilmeye karşı istikrarı azalır ve bu nesnenin zemin ile tam temasını kaybetmesine ve sallanmaya başlanmasına neden olur. Bu nedenle, deprem izolasyonu yapılmış müze binalarının içeriğini üç boyutlu deprem etkilerine karşı korumak için, düşey sismik izolasyon çözümü de temel seviyesinde devreye sokulmalıdır. Bu çalışma temel seviyesinde izole edilmiş müzelerde sergilenen antik heykellerin sismik korunması için düşey izolasyon cihazlarının performansını ölçmeyi amaçlamaktadır.

Anahtar Kelimeler: Düşey İzolasyon, Heykeler, Sallanma

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 directly transmitted to its contents. 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 motion. 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 a way, not to cause damage in its structure. Due to the vulnerable structure of ancient statues, which are often made of brittle material and already have cracks and defects due to the previous hazards in their life time, this energy input through such impacts, can cause irrecoverable damage, and sometimes even loss of this 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 earthquake excitations in every direction. In the following sections, the performance of the vertical seismic isolation devices on the seismic protection of a particular

ancient statue displayed in a base isolated museum building is presented. To achieve results, linear time history analyses are carried out with three dimensional earthquake ground motion input. The maximum accelerations of the three earthquakes used as input in the model can be seen in Table 1.

Table 1 Earthquake data used in the analyses

Earthquake	Longitudinal PGA (g)	Translational PGA (g)	Vertical PGA (g)
Athens 1999	0,84	1,01	1,20
El Centro 1940	0,31	0,22	0,21
Aquila 2009	0,41	0,44	0,49

The analyses are carried out in three stages. First, the acceleration time-history data of the earthquakes are applied to a 3 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 1. 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.

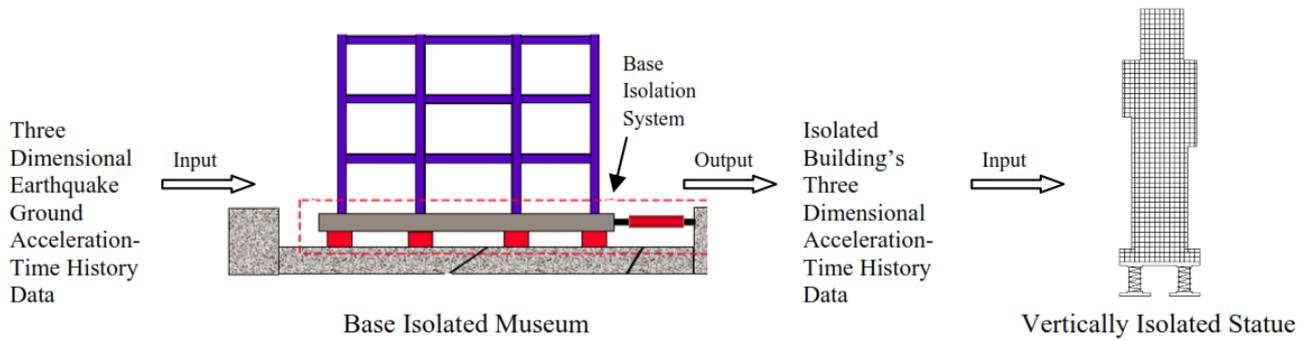


Figure 1. The general scheme of the analyses

2 Properties of the Museum Building Used In the Analyses

The museum building used in the analyses is modeled with friction pendulum isolator elements of low horizontal and high vertical stiffness. These isolation elements are used to increase the building's natural period under horizontal excitations. This way, the horizontal accelerations transmitted to the museum's structure and to its contents are reduced. From figure 2, the reduced frequencies and horizontal accelerations of the isolated museum building can be compared with the horizontal ground acceleration time history data of the Athens 1999 Earthquake.

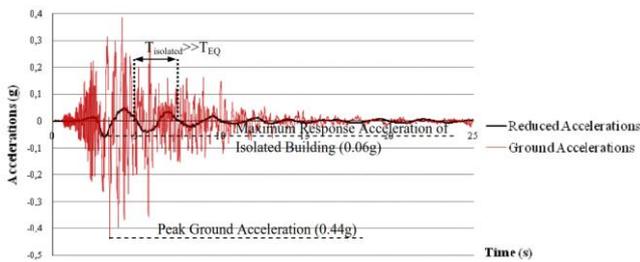


Figure 2. Time histories of the earthquake ground accelerations and response accelerations

Thanks to the low horizontal stiffness and high deformation capacity of the isolation devices, the building moves as a rigid body under horizontal excitations, and therefore the reduced horizontal maximum accelerations become practically equal at all the floors of the building, which may provide freedom for placing the statues at only floor, according to the preference of the museum curator. From figure 3, the amount of reductions in the accelerations at each floor can be observed, and compared with the maximum ground accelerations of the earthquakes.

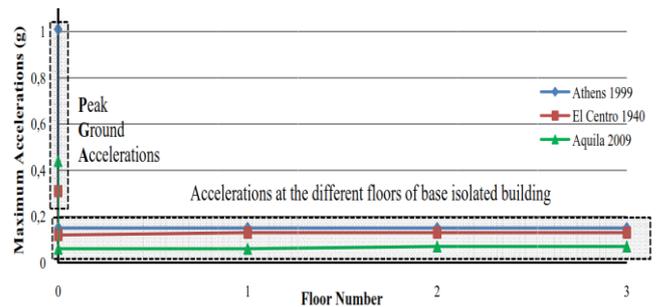


Figure 3. The reductions of horizontal accelerations in the base isolated building

3 Seismic Protection of an Ancient Statue Displayed In a Base Isolated Museum

The horizontal accelerations of the earthquakes can be reduced by increasing the building's natural period by means of horizontal isolation devices, thanks to their low horizontal stiffness and large deformation capacity. In figure 4, from the response spectra of 40 destructive earthquakes, it can be seen that reaching longer natural periods (more than 2 seconds), the horizontal response accelerations are reduced significantly.

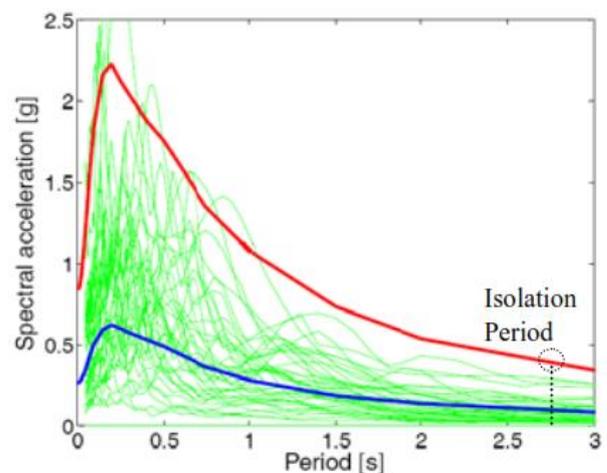


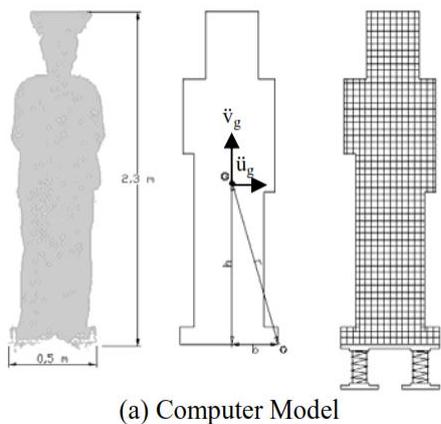
Figure 4. Horizontal Response Spectra of 40 records with $M \sim 7$ and $R = 10$ km [1]

Thus, it can be concluded that a statue inside a base isolated building is well protected against the horizontal earthquake excitations, if the isolation system of the building performs

successfully. However, since the isolation devices at the foundation level of the building have high rigidity in the vertical direction, the vertical accelerations of the earthquake are transmitted directly to the contents of the building. If the transmitted vertical accelerations are directed upwards, they reduce the stabilizing effect of the gravity on the statue, and eventually the statue becomes more vulnerable to the rocking motion. The impacts that the statue suffer during the rocking motion can cause substantial damage in its aged and already deteriorated structure. Therefore, to achieve an effective seismic protection for the art objects against three dimensional seismic actions, the effects of vertical accelerations on the objects stability should be investigated.

3.1 Computer Model

The computer model as shown in Figure 5.a, is composed of a finite element rigid block, which represents an ancient statue,



supported on vertical isolation elements. The statue above the vertical isolation level has a mass of 1500 kg, and it is able to rock over the constrained vertical isolation elements. The height of the center of gravity of the statue is 1.2 m, the half-length of its base is 0.25 m, and the distance between the centre of gravity and one corner is 1.23 m. In the analyses, the system is subjected to horizontal, \ddot{u}_g and vertical \ddot{v}_g accelerations at its base. The statue model is supported by four gap ("compression only") elements under its base, the behavior of which can be seen in Figure 5.b. The force deformation relationship of this element with stiffness k is given by equation 3.1 in the absence of damping [2].

$$f(x) = \begin{cases} k(d + open), & \text{if } d + open < 0 \\ 0, & \text{otherwise} \end{cases} \quad (3.1)$$

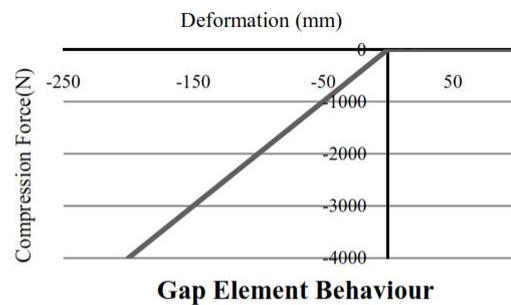


Figure 5. Computer model and the gap element

From Figure 5.b, the linear behavior of the gap elements can be observed. Note that these elements provide linear stiffness only under compressive loads. The isolation elements are rigid in the horizontal direction and show an elastic behavior in the vertical direction, in order to prevent the system from reaching a similar frequency content with the building's, which could cause high resonance displacements, and result in failure. Attention must be paid while choosing the isolator stiffness, in order to provide sufficient vertical bearing for the object, at the same time providing flexibility to reduce the effects of vertical excitations of earthquakes. The isolation elements used in the computer model satisfy this requirement. To observe the effect of vertical stiffness on the behavior of the statues, the analyses are carried out using different vertical isolator properties. From table 2, stiffness values of the vertical isolator elements can be seen.

Table 2 Stiffness properties of vertical isolators used in the model

Vertical Seismic Isolation Device	Vertical Linear Stiffness(k_v) (N/mm)
Vertical Isolator 1	100
Vertical Isolator 2	80
Vertical Isolator 3	60
Vertical Isolator 4	40
Vertical Isolator 5	20

3.2 Analysis Results

An effective vertical isolation system must be able to reduce the response accelerations by increasing the period of the dynamic response of the system, and controlling the response displacements simultaneously [3]. In general, as the isolation frequency decreases, the relative displacements increase and the response accelerations decrease. To achieve an effective isolation solution, keeping the relative displacements in a level that can be accommodated by the available isolation technology, the accelerations must be reduced as much as possible.

In the model, using four isolator elements of vertical stiffness of 20 N/mm, the first natural period of the statue becomes 0.84 seconds, in the vertical direction. For vertical component of the ground excitations which usually have higher frequency contents than the horizontal components, this magnitude of a natural period refers to the low band of spectral vertical accelerations. In Figure 6.a, the characteristics of the horizontal and vertical components of El Centro 1940 earthquake can be seen. From this Figure it is understood that with a vertical isolation period of 0.84 sec, as obtained in the analyses, the vertical accelerations can be reduced significantly. The maximum vertical accelerations observed at the statue model under three different earthquake time history records, in comparison with the peak vertical ground accelerations can be seen in Figure 6.b.

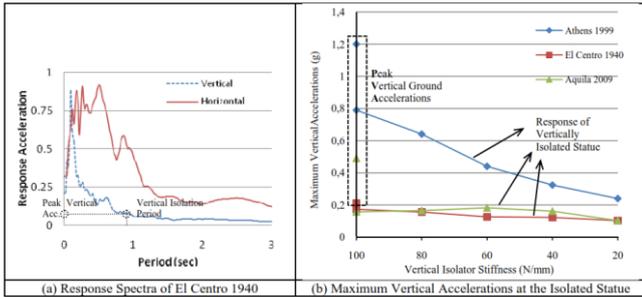


Figure 6. Horizontal and vertical response spectra of El Centro 1940 and vertical acceleration reduction graph

In table 3, for the three different earthquake records, the reductions of the vertical accelerations can be observed for a statue placed in a base isolated building and supported with four vertical isolator elements of 20 N/mm stiffness. As it is seen in the table, the reductions in the accelerations reach up to 90% in the horizontal and 80% in the vertical direction, thanks to combining vertical isolation elements at the base of the statue, with the base isolation system of the building.

Table 3 Reduction of vertical accelerations with vertical isolators of 20 N/mm stiffness.

Earthquake	Max Acc X-X (g)	Max Acc Y-Y (g)	Max Vertical Acc (g)
Athens 1999 / reduced by	0.14g / 80%	0.15g / 81%	0.24g / 80%
El Centro 1940 / reduced by	0.12g / 46%	0.11g / 41%	0.1g / 52%
Aquila 2009 / reduced by	0.06g / 81%	0.04g / 91%	0.1g / 79%

In Figure 7, the force-deformation behaviour of a vertical isolator element can be observed under three dimensional Athens 1999 earthquake excitation. As can be deduced from this Figure, the behaviour of the isolator element is quite close to linear, and it deforms in a hysteretic manner around an origin corresponding to its static state. It is important to note that, the deformations are always negative, which means the isolation element is under compression during the excitations, which is the expected behaviour of a “compression only” element. Also, it is important to note that the maximum vertical static and dynamic displacements observed at the isolation elements are compatible with the capacity of isolation devices that are currently available in the market.

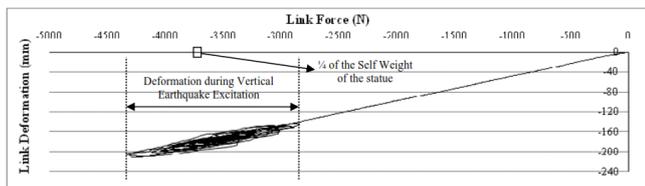


Figure 7. Vertical isolator force-deformation graph (Athens 1999 Earthquake) (Isolator Stiffness= 20 N/mm)

4 ROCKING ANALYSIS

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 8). 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 [4].

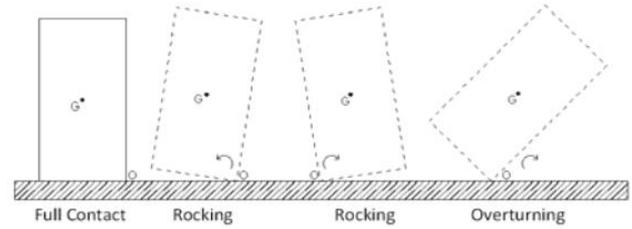


Figure 8. Rocking motion of a rigid block

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 to an ancient statue. 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. In order to define the level of allowable accelerations, the minimum impulse that can start the rocking motion of the statue is calculated, and compared with the “design impulse”, i.e. the impulse caused by maximum earthquake accelerations. The results of these calculations are presented as interaction diagrams between horizontal and vertical accelerations, for the specific ground motions. Examining these diagrams, the allowable horizontal and vertical accelerations under which the statue stays in full contact with the ground can be derived. The magnitude of minimum uplift impulse that causes rocking of the statue is obtained through the Equation (4.1) [5].

$$I_u = \frac{(1 \mp \frac{\ddot{V}g}{g})g}{\omega\lambda} \quad (4.1)$$

where ω is the natural frequency of the statue, $V \cdot g$ is the maximum earthquake acceleration (positive if it is directed downwards -same as gravity- and negative if it is directed upwards), g is the gravity acceleration in m/s^2 , and λ is the slenderness ratio (b/h). From this equation, it can be understood that the natural frequency, slenderness of the object and the vertical accelerations of the earthquake play a significant role on the resistance against rocking motion. Note that, the vertical accelerations directed upwards may considerably reduce the minimum impulse required for the uplift. The impulse caused by the horizontal earthquake forces shown in equation (4.2) can be estimated with the time integral shown in equation (4.3). The solution of this integral gives the value of “design impulse” caused by the earthquake forces. If the design impulse becomes larger than the minimum uplift impulse, the object loses its full contact with the ground and begins rocking.

$$\text{Earthquake force : } p(t) = m\ddot{u}_h(t) \quad (4.2)$$

$$\text{Magnitude of Design impulse : } \int_{t_1}^{t_2} p(t)dt \quad (4.3)$$

The magnitude of the triangular area that is drawn between two consecutive time instants, corresponding to the maximum horizontal acceleration in the time history diagram of Figure 9 gives a reasonable estimate for the magnitude of “design impulse” for unit mass. It can be calculated with the expression

(4.4). From the same Figure the frequency that should be taken into account for the calculation of minimum impulse can also be decided.

Design Impulse for unit mass : $I_d = a_{max} \cdot \frac{1}{2} \cdot (t_2 - t_1)$ (4.4)

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

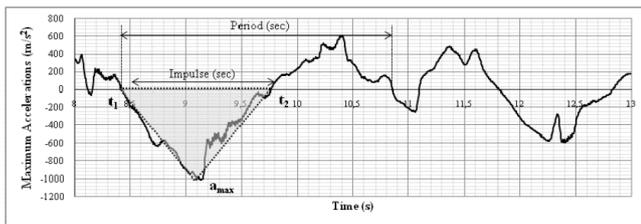


Figure 9. A portion of the acceleration time history graph used for the calculation of design impulse

For instance, when a maximum horizontal acceleration of 0.15g and vertical acceleration of 0.24g are considered (as obtained under the three dimensional earthquake excitations of Athens 1999 Earthquake, for a vertically isolated statue placed in a base isolated building), the results of the calculations show that the “design impulse” remains lower than the minimum uplift impulse and the object stays in full contact with the ground. However, if the vertical isolation system is not provided for the same case, the design impulse of the same earthquake exceeds the minimum uplift impulse, and the object starts rocking even with slight horizontal accelerations.

The results of the calculations are represented as interaction diagrams as shown in Figure 10. In this Figure, the trend line shows the intersection between the magnitudes of maximum horizontal and vertical accelerations, below which the statue stays in full contact with the ground, during the Athens 1999 Earthquake. The points above the trend line show the acceleration values that are sufficient to start the rocking motion. From this Figure, it can be seen that with a proper vertical isolation solution, the accelerations that the statue experience in a horizontally isolated building can be reduced enough so that it stays in full contact with the ground. The results obtained in this study may easily be extended to the other cases with different ground motions and art objects with different geometric properties.

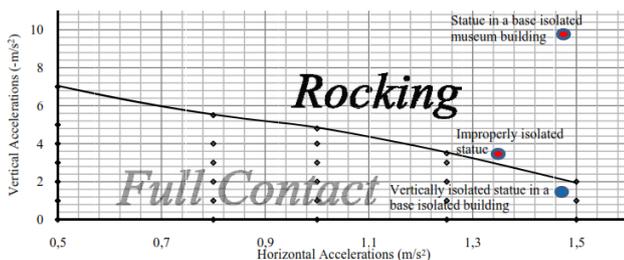


Figure 10. Interaction diagram of permissible horizontal and vertical accelerations for Athens 1999 Earthquake

5 CONCLUSIONS

In this paper, the contribution of vertical isolation devices to the seismic protection of an ancient statue is investigated. To carry out dynamic analyses on the ancient statue, first the acceleration time history data of three different earthquakes are applied to a reinforced concrete structure that can represent a base isolated museum building. Then, linear time history analyses are performed on a rigid block, which has the simplified geometry of an ancient statue supported on vertical isolation devices. As a result, it is seen that both, the horizontal and vertical accelerations transmitted to the statue can be reduced significantly, thanks to the combination of vertical isolators at the base of the statue with the horizontal base isolation system of the building. Assessment of the rocking conditions is carried out, in order to evaluate the allowable accelerations under which the statue remains in full contact with the ground, and suffers no damage due to the impacts during rocking. Comparing the design impulse, caused by earthquake forces, with the minimum uplift impulse of the statue, the combinations of horizontal and vertical acceleration components that either let the statue stay in full contact or lead to start rocking motion are presented in the form of interaction diagrams. It is shown that, using suitable isolation devices, an ancient statue displayed in a base isolated museum building can be protected efficiently against three dimensional earthquake excitations.

6. REFERENCES

- [1] Baker J. W. and Cornell C.A., "Spectral shape, epsilon and record selection," *Earthquake Engineering & Structural Dynamics*, vol. 35, no. 9, p. 1077–1095, 2006.
- [2] Wilson, Edward L. *Three Dimensional Static and Dynamic Analyses of Structures, A Physical Approach on Earthquake Engineering*, California, USA: Computers and Structures, Inc, Berkeley, 2002.
- [3] Kitamura, S. and Morishita, M., "Design Method of Vertical Component Isolation System," *Transactions SMIRT*, p. paper #1264, 2001.
- [4] Oliveto, G., Calio, I., Greco, A., "Large Displacement Behavior of a Structural Model with Foundation Uplift under Impulsive and Earthquake Excitations" *Earthquake Engineering and Structural Dynamics*, vol. 32, John Wiley & Sons, Ltd., 2002, pp. 369-393.
- [5] Calio, I., Marletta M., "Passive Control of the Seismic Rocking Response of Art Objects," *Engineering Structures*, no. 32, pp. 1009-1018,, 2003.