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Original article

# Application of predictive models to assess failure of museum artifacts under seismic loads

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## ABSTRACT

In recent years, there has been a growing interest in the protection of cultural heritage structures and artifacts from seismic excitations. Nevertheless, although the vulnerability of museum exhibits under seismic excitations has been repeatedly verified, it has not been given proper attention. In this work, emphasis is placed on efforts for mitigating seismic risk of museum artifacts elucidating the necessity to identify artifact failure not only based on code design spectra that mainly account for far-fault conditions but also considering near-source phenomena. A general methodology is proposed and demonstrated with representative examples. The methodology considers the detailed geometry of the artifacts, its support conditions, relative distance from the soil surface, the fundamental frequency of the housing structure as well as relevant seismological data, such as vicinity with active faults and soil type, and provides the critical distance from an active fault within which the artifact could fail. The proposed methodology can serve as an easy-to-apply analytical means to assess the seismic risk of museum exhibits for preserving cultural heritage.

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*Abbreviations:* $\alpha$, angle of the rigid block given by the arctan(B/H); $a_g$, peak ground acceleration for ground type $A$; $\bar{a}$, ratio of $a_g$ to the acceleration of gravity $g$; $a_g^h$, horizontal acceleration at the base of a rocking body; $\gamma_a$, importance factor of a non-structural component; $\mu$, mean value; $\theta$, angle of the rigid block from the vertical; $\sigma$, standard deviation; $T_K$, parameter related to the incremental change to the kinetic energy of a slender rocking body; $\varphi_I$, parameter related to the dynamic response of a slender rocking body (refer to Eqn. (12)); $\varphi$(y), normal mode shape of a slender rocking body; ω, fundamental natural circular frequency; $b$, half-width of the rigid block; $B$, total width of the rigid block; $CM$, center of mass; $D$, total depth of the rigid block; $E$, Young's modulus; $g$, acceleration of gravity; $h$, half-height of the rigid block; $H$, total height of a rigid block or a slender rocking body; $H'$, equivalent height; $\bar{H}$, total height of the structure above the level of application of the base shear; $i$, radius of gyration; $I$, second moment of area; $I_0$, mass moment of inertia of the rigid block about point 0 or 0' (refer to Fig. 5); $I_0^{CM}$, mass moment of inertia around an axis that passes through the center of mass; $K_e$, parameter related to the dynamic response of a slender rocking body (refer to Eqn. (12)); $M$, total mass; $\bar{m}$, mass per unit length; $m^*$, parameter related to the dynamic response of a slender rocking body (refer to Eqn. (12)); $M_L$, local earthquake magnitude; $M_S$, surface earthquake magnitude; $M_W$, moment earthquake magnitude; PGA, peak ground acceleration; PGV, peak ground velocity; $p$, parameter of the dynamic response of a rigid block (see Eqn. (4)); $q_a$, behavior factor of a non-structural component; $r_m$, distance from the axis of rotation to a mass element dm; $R$, distance from point $0$ to the center of mass, $R = \sqrt{b^2 + h^2}$(refer to Fig. 5); $R_{jb}$, distance from the surface projection of a seismic fault (Joyner-Boore distance); $R_{max}$, critical distance for failure; $S$, soil factor; $S_a$, seismic coefficient; $S_{vo}$, spectral velocity required to cause overturning; $T_a$, fundamental vibration period of a non-structural component; $T_n$, fundamental vibration period of a structure; $v_g^h$, horizontal velocity at the base of a rocking body; $V$, total volume; $v_{S,30}$, average shear wave velocity in the upper 30 m of the soil profile; $z$, the height from the level of the application of base shear to the center of mass of the non-structural component; $W$, total weight; $W_a$, artifact weight; $W_p$, pedestal weight.

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## 1. Research aims

This work presents a simple methodology that allows assessing seismic risk for museum artifacts. According to the proposed procedure, the maximum distance from an active fault is defined, within which the artifact is threatened by failure either because of rocking or overturning. The calculation of this "critical distance" is performed considering the geometry and mass of the artifact, the support conditions, the soil conditions at the site and the special characteristics of strong ground motion at small distances from active faults; namely, near-fault phenomena.

The proposed procedure can be used as a means to engineer protection measures of cultural heritage assets in museums at seismic prone regions. Representative museum artifacts placed in the National Museum of Athens, Greece, are selected as case studies and the reliability of the procedure is verified based on failures observed after three significant earthquake events in Greece.

## 2. Introduction

Eastern Mediterranean countries such as, Greece, Italy, Cyprus and Turkey, are well known not only for the noteworthy history of the native civilizations but also for their high seismic activity [1].

Recently there has been increased concern on a global scale for the protection of museum artifacts from seismic threats, after the failure of significant exhibits from major devastating earthquake events, such as: (i) the 17th August 1999 Izmit (Kocaeli) $M_W = 7.5$ and the 12th November 1999 Duzce $M_W = 7.1$ earthquakes in Turkey that caused extensive damage to monuments and historic structures [2]; (ii) the $M_W = 6.3$ earthquake in L'Aquila, Italy on April 6, 2009 that caused extended failure not only to numerous historic and monumental structures but also to the contents of the National Museum of Abruzzo [3] and (iii) the $M_S = 6.0$ and $M_S = 6.1$ earthquakes that occurred on January 26th and February 3rd, 2014, respectively, in Cephalonia, Greece and caused significant damage to museum artifacts in the Archaeological Museum of Argostolion.

Unfortunately, there is a lack of seismic regulations regarding the protection of museum artifacts even in countries with high seismic activity. Usually museum artifacts are treated as non-structural components in light of provisional requirements [4–7] since they do not constitute a bearing part of the structure. Some easy-to-apply directives are also available in the literature for the support of museum artifacts, e.g., [8,9], while the experimental work in this area remains limited, e.g., [10]. The available directives generally include simple analytical calculations related to stability and empirical rules to form the artifact supports based on the type of the artifact and its constituent material [9].

A typical procedure to design the supports for non-structural acceleration sensitive components is the development of approximate floor acceleration spectra, e.g., [11]. Caution should be paid to the amplification of floor accelerations caused by higher mode effects that should be considered in the design [12].

The current European seismic code, Eurocode 8, EC8, [13] suggests that the design of non-structural components should be based on the force $F_a$ that is applied at the center of gravity of the object and may be calculated by the following formula:

$$F_a = (S_a \cdot W_a \cdot \gamma_a)/q_a \tag{1}$$

where $S_a$ is the seismic coefficient, $W$ is the weight of the component, $\gamma_a$ is its importance factor varying between 1.0 and 1.5, and $q_a$ is the behavior factor of the component that varies between 1.0 and 2.0. Eurocode 8 [13] accepts that a non-structural component can be designed to respond inelastically depending on its type. The behavior factor $q_a$ is a reduction factor applied to the seismic forces accounting for the nonlinear behavior of the component (artifact). The seismic coefficient $S_a$ is the design seismic acceleration of the non-structural component divided by the acceleration of gravity and can be calculated from:

$$S_a = \bar{a} \cdot S \cdot \left[ \frac{3\left(1+\frac{z}{H}\right)}{1+\left(1-\frac{T_a}{T_n}\right)^2} - 0.5 \right] \geq \bar{a} \cdot S \tag{2}$$

where $\bar{a} = a_g/g$ is the ratio of peak ground acceleration for ground type $A$, $a_g$, to the acceleration of gravity $g$, $S$ is the soil factor, $T_a$ is the fundamental vibration period of the component, $T_n$ is the fundamental vibration period of the structure in the considered direction, $z$ is the height from the level of the application of base shear to the center of mass of the component and $H$ is the total height of the structure within which the non-structural component is placed above the level of the application of base shear. Ground type A according to EC8 [13] refers to a stratigraphic profile with an average value of shear wave velocity in the upper 30 m of the profile $v_{S,30} > 800$ m/s.

The most widely used approaches for the protection of artifacts are: (i) fixing of the base, and (ii) base isolation. The use of isolators for museum artifacts, even though well studied [e.g., 14–17], is a technology that has been applied in practice only to a limited extend, e.g., [18]. Recent unpublished experimental and analytical research performed at the Laboratory for Earthquake Engineering of the National Technical University of Athens (LEE-NTUA) on artifacts and showcases to be placed at the Louvre-Abu-Dhabi museum has revealed the advantages and disadvantages of both approaches [19].

In the literature the study of the seismic response of artifacts with analytical means is more extended compared to the available experimental results [20–24], while there exist only limited research that combines experimental and analytical work, e.g., [25].

The dynamic response of a museum artifact simply supported can be studied with the equations of motion describing the response of a single or multiple blocks under ground excitation. From that point of view, a large number of formulations and analytical and numerical solutions may be found in the literature for the governing nonlinear equations for rocking motion of single or multiple rigid blocks, e.g., [26–31] as well as slender structures allowed to overturn [32].

In the present investigation, previous work of the authors [20–22] is extended regarding the vulnerability of museum artifacts under seismic excitation with emphasis on near-fault seismic motions. A number of representative museum artifacts placed in the National Museum of Athens are selected and simplified criteria are used in order to define the acceleration and velocity required to cause failure. Then applying recent attenuation relationships that consider near-fault effects, the minimum distance needed to provoke failure as well as the type of failure is determined for every artifact. Finally, the results of the procedure are verified based on representative case studies of significant earthquake events.

## 3. Seismicity in Greece with emphasis on damage of artifacts

The particular vulnerability of artwork to seismic excitations in Greece, regarding the historic years, has been recognized through paleoseismological, archaeological and historical studies, e.g., [33,34]. During modern years, the vulnerability of museum artifacts was re-confirmed. Representative strong earthquakes during the last decade are listed in Table 1, in terms of the surface wave magnitude scale $M_S$. Damages of both the museums and their artifacts have been observed in all cases.

Referring to the $M_L = 6.7$ Alkyonides earthquake on February 24, 1981, dramatic artifact failures were recorded at the Perachora Museum, located a few kilometers from the epicenter [35], (Fig. 1).

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