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GUIDELINES FOR SEISMIC PROTECTION OF MUSEUM CONTENTS

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ABSTRACT

With regard to the preservation of the cultural heritage, the contents of Museums appear at least as important as monumental buildings, to which much more attention has been paid in the earthquake engineering literature. This paper summarizes and completes previous researches on the seismic response of *art objects* exhibited in Museums, and presents simple, low-cost rules for reducing the risk of damage in case of a medium-intensity earthquake (provided that the containing building is not too severely damaged). The application of the rules is illustrated with specific reference to an Archaeological Museum to be set up in Irpinia, a region of Southern Italy hit by many severe historical earthquakes (the last significant one in 1980). To obtain reliable indications, the input seismic motion at the building foundation level must be filtered through the building structure and, if present, the structure of the exhibition case: some alteration of the latter can indeed provide much of the protection needed for the exhibited objects.

KEYWORDS

Cultural heritage; Museums; works of art; seismic input; seismic design; seismic protection; rigid-body motion; stick-and-slip motion; rigid-body oscillations.

INTRODUCTION

In recent years, many studies have been devoted to the seismic protection of existing buildings and in particular of monumental buildings, as a facet of the worldwide developing interest for the conservation of the cultural heritage: specific techniques and strategies have been elaborated for their safeguard. On the contrary, the protection of the contents of Museums (denoted *art objects* in the following), although at least as important as that of buildings in this respect, has received much less attention in the earthquake-engineering research literature, probably because of the very few occasions that Structural Engineering researchers and Museum designers and trustees have to meet with each other.

This paper, that intends to be a step towards filling this gap, summarizes and completes a series of already published results (Augusti *et al.*, 1992-1995). It deals in particular with the formulation of simple low-cost rules and prescriptions able to reduce the risk of damage of *art objects* in case of an earthquake (provided of course that the containing building is not too severely damaged). It is indeed an obvious fact that the enormous number of objects to be protected does not make it feasible (and not only for reason of excessive costs) to implement specific risk-reduction devices for each objects: the use of base isolators or similar devices must therefore be limited to single objects of very high value in high seismic risk situations.

SEISMIC RISK OF ART OBJECTS

The seismic action is transmitted to the *art object* by its support or restraint. As a preliminary operation, the significant characteristics must be assessed of the earthquake-generated motion at the level of the relevant exhibition floor: at the very least, effective peak horizontal acceleration a_g and velocity v_g corresponding to a *reasonably severe* earthquake (*design earthquake*, often indicated by Building Codes) are necessary but, as it will be seen in the following, in many case complete seismic histories are required.

The acceleration histories at ground level can be obtained (taking account of the seismicity and geology of the building site) by generating a sufficient number of simulated accelerograms consistent with a response spectrum appropriate for the specific soil condition, possibly in accord with instructions given by Building Codes. However, the *filtering action* of the structure interposed between the ground and the object support (always a building, and often also an exhibition case) affects significantly the actual magnitude and spectral characteristics of the action on the *art object*. Therefore, each accelerogram must be filtered through the structure of the building (to consider a linear elastic building is in general a safe assumption with regard to peak values of acceleration a_g and velocity v_g) and of the exhibition case, if existing, and then integrated to obtain the velocity v.This is a key point because, while in general the Museum designer has little power with regard to the structural design of the building, he may have a great influence on the design of the exhibition cases, which affects at least as much the action on the *art objects*.

Art objects are typically delicate: therefore, the maximum stress should always be checked to ensure the resistance of the constituent material(s). If the object can move with respect to the restraint or support, this stress may be reduced, sometimes to the point of becoming irrelevant, but the largest displacements under the design earthquake must be limited in order to avoid impacts and failures: this situation may be quite normal (hanging *oscillating* objects) or be artificially created by reducing the friction (supported *sliding* object).

These introductory considerations make it evident that the development of guidelines of general validity for the seismic protection of *art objects* requires some preliminary broad classification with respect to the main features of their seismic response and possible causes of damages: the most important division is between objects supported on a horizontal plane (on a floor of the building, within an exhibition case, etc.) and suspended or hanging objects (e.g. paintings). Such a classification, a revised version of the one first presented by Agbabian *et al.* (1990) and already modified by Augusti *et al.* (1993a), is reported in Tables 1 and 2, respectively with regard to the main types of *art objects* and their form of support or restraint.

Table 1. Art object typological categories

T1	*small, flat-bottomed*
T2	*small, not flat-bottomed*
T3	*statues, sculptures and large vases*
T4	*paintings and panels*
T5	*chandeliers*
T6	*miscellanea*

In the left section of Table 3, the possible forms of motion are listed for each support/restraint category. Note in particular that objects belonging to category A of Table 2 (*freely supported objects*, which perhaps comprise the largest number of Museum exhibits) can respond in several different ways, according to the conditions indicated by α, β, γ in Table 3 (g is the acceleration of gravity), and also plotted in Fig.1, which will be discussed below.

Table 2. Support/restraint in relation to categories

	A *objects supported on a flat plane*				B *objects fixed on a flat plane or on a pedestal*	C *suspended/hanging objects*	
	A1 *on the floor*	A2 *on a pedestal*	A3 *in display cases*	A4 *on cantilever or in wall cases*		C1 *suspended on a wall*	C2 *hanging from the ceiling*
T1	*	*	*	*	*		
T2	*	*	*	*	*		
T3	*	*			*		
T4						*	
T5							*
T6	*	*	*	*	*	*	*

DEVICES AND INTERVENTIONS

The relevant possible mechanism of damage or failure is reported in the right section of Table 3, in correspondence of each form of motion in the left section. The safeguard measures and devices (I1, I2, ...) are described in Table 4; those apt to avoid each mechanism are indicated above it, by filling the corresponding box with a number (1, 2, ...) that suggests an order in which they can be tried or applied.

As indicated in Table 4, the application of the safeguard measures implies the use of operative diagrams, which are specific for the site, the Museum building and, possibly, the exhibition case. Typical diagrams are presented in Figs.1-5. They have been derived with reference to a specific example: an Archaeological Museum which is being set up in a 16th Century building, recently restored to this purpose, located in Altavilla Irpina, in a region of Southern Italy that has been hit by many severe historical earthquakes up to MM intensity 7-8 (the last significant one in 1980) (Augusti and Ciampoli., 1995a, b).

Diagram D1 (Fig.1) identifies the regions of alternative dynamic responses of objects belonging to Category A, in function of the width 2B of the object base and the height H of the centroid above the supporting plane, as discussed in detail in Augusti *et al.* (1992a, 1993a, b). The solid lines represent the limit of validity respectively of the conditions α and γ of Table 3, that express the well known Ishiyama's criteria (Agbabian *et al.*, 1990), relevant to objects that do not slide, namely: if the aspect ratio B/H is smaller than a_g/g (condition α), the object oscillates alternatively about the two edges of the base, impacting on the supporting plane at each change of rotation axis; it may overturn if the base velocity v_g is sufficiently large (condition γ). Such oscillations on the supporting plane must absolutely be avoided, not only because of possible overturning, but also because the associated repeated impacts may cause severe damage: therefore, devices I3 and/or I4 aim at bringing the point (B, H) above the line $B/H = a_g/g$, so that - apart from sliding - the object would remain stuck on the supporting plane, as if belonging to category B. At first sight, this last condition may appear the most convenient, but it can be associated to large accelerations, hence to large inertia forces and consequent stresses. However, if the friction coefficient μ is smaller than a_g/g , the object slides (condition β): a cutoff on the object acceleration is always given by μg, and the reduction of μ (device I2) can be used as a safeguard against excessive stresses. The line μ = B/H (dotted in Fig.1) divides the B, H plane into regions of possible sliding (R2) and rocking motions (R3-R4): if it falls below the line $B/H = a_g/g$, the object is never "stuck", and its expected displacement must be checked by *Diagram D2* (see below). Note that Ishiyama's criteria can be accepted in practical applications for their simplicity and their acceptable agreement with experimental results, all the more because oscillations must be avoided, and only condition α really matters. The plots in Fig.1 depend on the values of a_g and v_g, and must be calibrated for the different buildings, floors and exhibition cases.

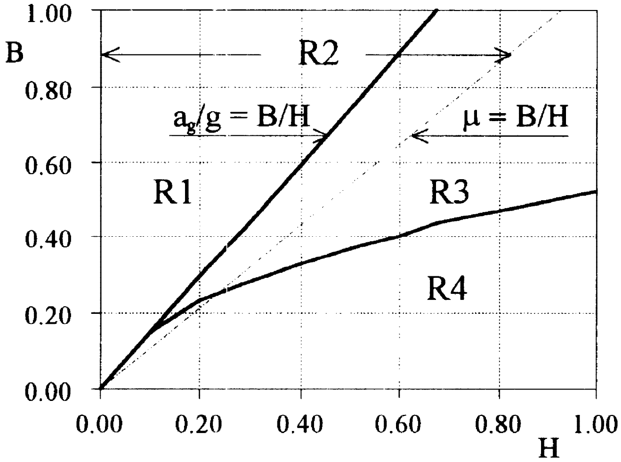


Fig.1. *Diagram D1*: typical response regions of a rigid object (base width 2B; height of centroid H) supported on a horizontal plane (cf. Table 3)

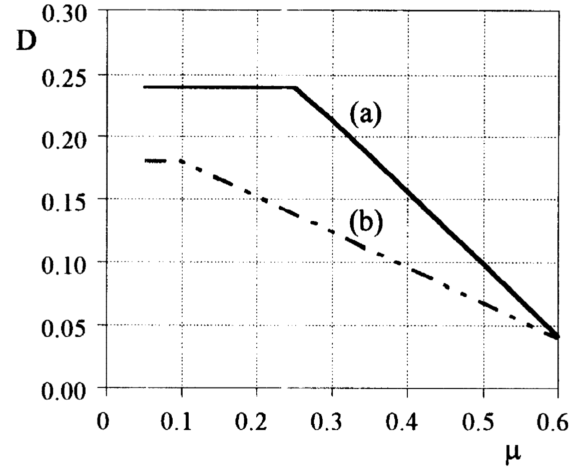


Fig.2. *Diagram D2*: required clearances of sliding objects: (a) on the top slab of a case; (b) on the floor

Diagram D2 yields the minimum clearances between sliding objects vs. the friction coefficient μ, with reference to objects standing respectively on the top slab of a typical exhibition case (curve *a*) and on the floor of a Museum show room (curve *b*). These linearized plots are a safe approximation of the 84% fractiles of the distribution of the maximum values of displacements, evaluated by considering an appropriate number of bidimensional time-histories, as illustrated in detail in Augusti and Ciampoli (1995a, b).

The vertical component of the seismic action could be very dangerous for supported objects, because of the reduction in the friction force. Therefore, cantilevered supports (including wall cases) must be avoided: in this case, the vertical component can usually be neglected (Augusti and Ciampoli, 1993c).

As already indicated, the structure of the exhibition case affects in a significant way the characteristics of the motion of the supporting plane: typically, a flexible case reduces the acceleration a_g and velocity v_g, hence the stress in non-sliding objects, but increases displacements of sliding objects. Therefore, appropriate care should be taken - at very little cost! - in the preliminary design of the cases; alternatively, modifications of the structure of existing cases can greatly improve the situation (Augusti *et al.*, 1992a, 1993a). A systematic investigation on the *best* characteristics of the cases has not yet been performed, but it appears already fair to state that, as a rule, they should have a compact shape, comparatively high stiffness, light support planes, and be bolted on the floor to avoid overturning.

In special cases (I5 and I6 devices), the acceleration at the base of the object must be reduced by isolating/dissipating devices (*isolators*), in order to keep the stress below an acceptable level. The required factor of reduction η of the acceleration transmitted to the object is given by the resistance check I1: its attainment must be checked on the efficiency diagram of the isolator.

In Fig.3 (*Diagram D3*), a typical acceleration response spectrum for a rotational rubber base isolator is shown, while in Fig.4 (*Diagram D4*) a typical example of the isolator efficiency diagram is given with reference to the mechanical base isolator considered by Augusti and Ciampoli (1995a, b).

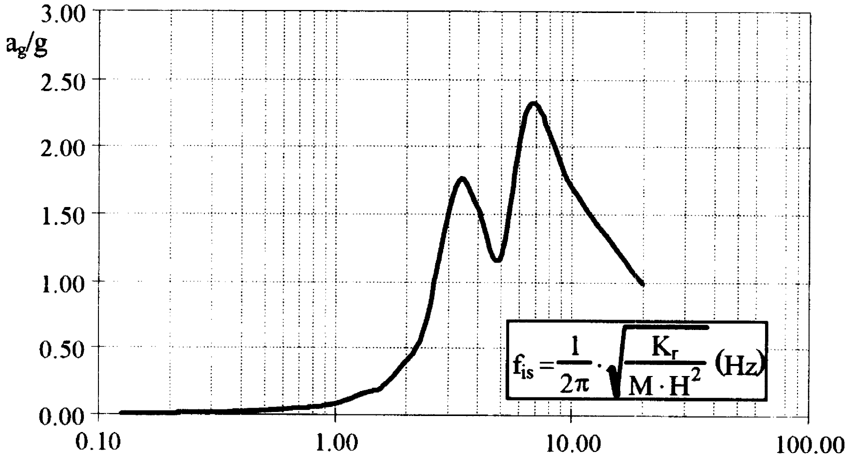


Fig.3. *Diagram D3*: acceleration response spectrum of an art object on a rotational base isolator (K_r = rotational spring constant), subjected to a given base motion history (Augusti and Ciampoli, 1995a, b)

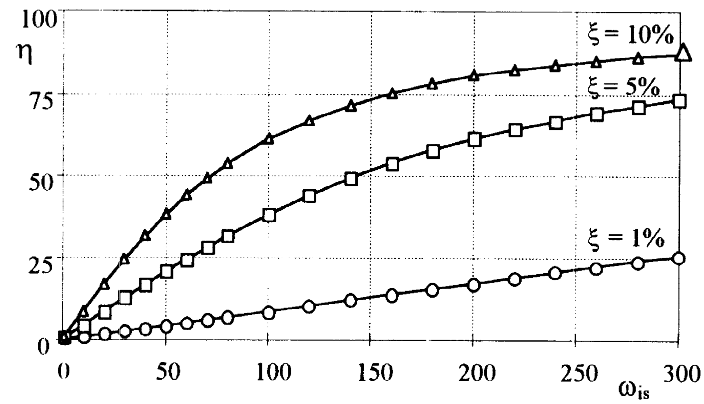


Fig.4. *Diagram D4*: reduction factors of the peak acceleration transmitted by a mechanical isolator (Augusti and Ciampoli, 1995a, b) vs. the frequency of the system art object+isolator, as a function of the damping coefficient of the base isolator

In the case of objects hanging from the ceiling or suspended in contact with a wall, the additional stress due to an oscillation of the building is in most cases irrelevant, but the displacements must be checked (I7 and I8 devices). The plots in Fig.5 (*Diagram D5*) yield the acceptable clearances X between suspended objects: ν is an equivalent damping coefficient, function of the friction coefficient between the object and the wall (Augusti and Ciampoli, 1995a, b). For hanging object, curve *a* in Fig.5 can be used, but the value of X must be incremented by 40% to take into account the bidirectionality of the motion.

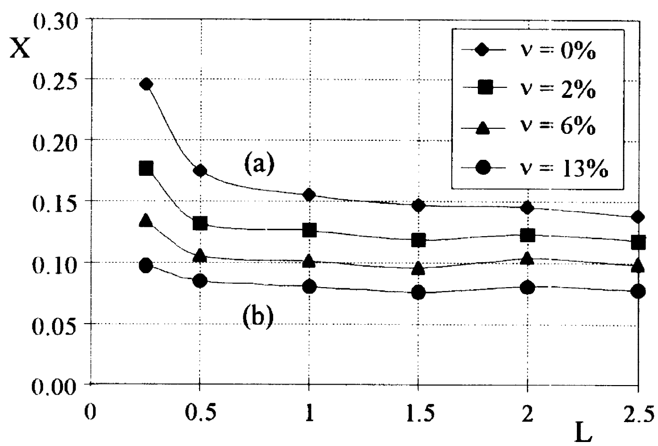
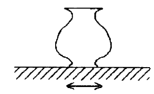
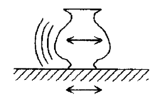
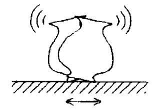
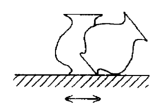
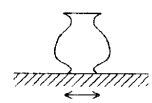
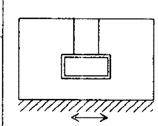
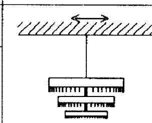
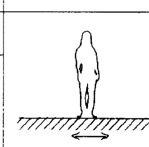
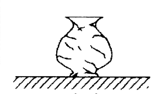


Fig.5. *Diagram D5*: maximum displacements of suspended objects vs. hanger length L, for different values of the equivalent damping coefficient (Augusti and Ciampoli, 1995a, b)

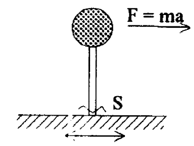
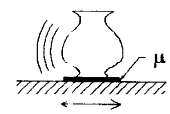
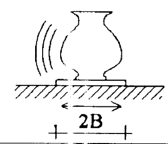
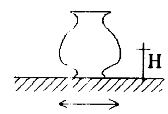
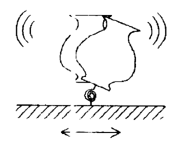
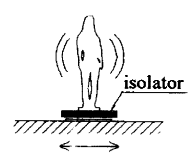
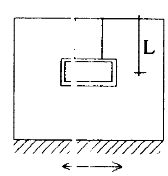
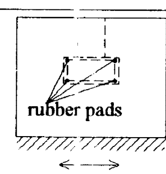
Table 3. Support/restraint vs. types of dynamic response and safeguard interventions

	POSSIBLE MOTIONS AND ASSOCIATED CONDITIONS				INTERVENTIONS (IN SEQUENCE) AND DAMAGE/FAILURE MECHANISMS								
	Type	α	β	γ	I1	I2	I3	I4	I5	I6	I7	I8	
A	R1	NO	NO	-	1	2			3				
		stick motion			*excessive stress*								
	R2	-	YES	-	1	2			3				
		sliding motion			*excessive displacements*								
	R3	YES	NO	NO	4	1	2	3	5				
		oscillations			*repeated impacts*								
	R4	YES	NO	YES	4	1	2	3	5				
		overturning			*overturning*								
B	R1	-	-	-	1	3			2				
		stick motion			*excessive stress*								
C	R5	-	YES	-							1	2	
		sliding motion			*excessive displacements*								
	R6	-	-	-							1		
		oscillations			*excessive displacements*								
Special cases	R3-R4	YES	?	?						1			
		oscillations overturning			*excessive stress, repeated impacts*								
	R3-R4	YES	?	?					1				
		oscillations overturning			*excessive stress, repeated impacts*								

α	$\frac{a_g}{g} > \frac{B}{H}$
β	$\frac{a_g}{g} > \mu$
γ	$v_g > \frac{10\,B}{\sqrt{H}}$

YES ⇒ SATISFIED	
NO ⇒ UNSATISFIED	
- ⇒ IRRELEVANT	

Table 4. Description of checks and interventions on the art objects

I1	*The resistance of the critical points (e.g. the section S) is checked.*	
I2	*The friction between the base of the object and the supporting plane is reduced by interponing a special material like teflon; the value of the safety distance is given by D2.*	
I3	*The base 2B of the object is widened by means of a special device (Fig.1) until the characteristic point (B, H) falls above the solid straight line in D1.*	
I4	*The center of mass of the object is lowered (e.g. by filling a vase with sand) until the characteristic point (B, H) falls above the solid straight line in D1.*	
I5	*A natural or synthetic rubber isolator is introduced; its efficiency is diagrammed in D3.*	
I6	*A mechanical isolator is introduced: its efficiency is evaluated by means of D4.*	
I7	*The length of the hangers is chosen such to limit the inertia force in the object; the safety distance is evaluated by means of D5.*	
I8	*In addition to I7, rubber pads are interponed between the object and the wall; the safety distance is evaluated by means of D5.*	

OPERATIVE GUIDELINES

In short, the procedure for recognizing the motion and possible damage mechanisms, and choosing the checks and devices to safeguard each *art object*, can be summarized in the following steps:

- prerequisite: *obtain the relevant values of a_g and v_g and the operative diagrams D1-D5*
- *identify the typological category (T1-T6, Table 1)*
- *identify the restraint or support condition (Table 2; Table 3, first column)*

- *check the conditions in Table 3, second column, and consequently identify motion and damage mechanism*
- *apply, in the order indicated in Table 3, the checks and devices described in Table 4, until the behaviour is satisfactory*

Modifications of the preliminary design of the exhibition cases or of their existing properties are other low-cost devices to improve the seismic response and increase the reliability of art objects; they obviously imply to repeat the calculations leading to a_g, v_g and D1-D2.

SOME CONCLUDING REMARKS

Simple devices for reducing the risk of damage of *art objects* in case of an earthquake (of course within a building that is not too severely damaged) have been presented in a form such that they could be implemented even by people without specific knowledge of earthquake engineering, provided that the seismicity and geology of the site have been carefully assessed, and reliable operative diagrams have been plotted. It can be stated that, if applied during the design stage of an exhibition, the cost of these devices is practically nil: but they may cost very little also when applied to improve an existing situation.

Operative diagrams have been derived and presented for a case example: it is hoped that this, and other examples, can find actual application.

It has been underlined that the structures interposed between the foundation and the exhibited object filter significantly the ground motion. One of these structures may be an exhibition case: considering that in general a Museum designer has little power with regard to the structure of the building, while he may have a great influence on the form of the exhibition cases, an appropriate design of the latter (or their modification for existing Museums) can be essential for the stated aims. Therefore, as the next step in this research, a systematic investigation on the *best* characteristics of Museum exhibition cases is planned.

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