EVALUATION OF EARTHQUAKE DAMAGE MITIGATION METHODS FOR MUSEUM OBJECTS

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Act—In this paper, procedures are discussed for the evaluation of some of the earthquake damage mitigation methods in use or under development at the J. Paul Getty Museum. Generic models for various categories of objects have been formulated and analytical techniques have been devised that allow the assessment of the susceptibility of objects to rocking, overturning, sliding, and stress failure when subjected to earthquake-induced forces. Failure criteria are discussed and examples of categories of mechanical methods for reducing transmitted forces are given. Experimental verification of some of the analytical formulations has been carried out on object models using sine, swept sine, and simulated earthquake accelerogram inputs to laboratory-scale shake tables. The concepts and procedures described are generally applicable to other museums and cultural heritage repositories.

1 Introduction

The possibility of damage to fragile objects on display in museums during an earthquake is significant even if the building structure itself remains intact. Violent shaking and tilting of rigid structures can lead to object overturn, fracture resulting from dynamic loading stresses, or sliding and collision of the object with neighboring objects or walls. The damage resistance of objects depends on many factors including earthquake characteristics, building response, object materials properties and structures and support method. Although resistance to damage can be improved by modifications either to the object or to its support, altering the support is the preferred method.

Development of techniques for mounting objects in museums located in areas of seismic activity has not received much organized attention by the conservation community. This lack of activity may have been due to the relatively low priority given the problem because of the infrequency of earthquake occurrence. Another possible reason is the wide variation in object characteristics that need to be addressed in the design of a mounting system and in the absence of useable guides that relate these characteristics to the failure mechanisms that are applicable during an earthquake.

Methods for protecting the contents of buildings from earthquake damage have been described [1–3] but these are essentially qualitative and do not take into consideration the special needs that exist for the protection of museum objects. These include minimum intervention with the object itself and with its appearance.

Several years ago, the staff of the J. Paul Getty Museum (JPGM) in California recognized these problems and initiated design studies of mounting systems that would assure survival of objects in the event of an earthquake on the nearby Malibu fault. The systems that were developed ranged from a sophisticated base isolation system for a marble Kouros [4] to simple, unobtrusive tie-down clamps. However, a need existed both for a quantitative evaluation of the performance of the combined object-support systems when subjected to an earthquake, and for engineering guidelines that could be applied to the design of the mounts for the other objects in the collection.

In this paper, we report on the development of a procedure for evaluation of the response of individual art objects to earthquake excitation. To accomplish this, it was found expedient to generalize and use generic object classifications because of the large variety of objects and support systems that required analysis. The generic systems considered included the six most often encountered object/support systems and three types of base isolation systems. Analytical studies were carried out to model the systems and to determine significant system parameters. A number of experimental tests were performed to determine the validity of the analytical models by subjecting physical models to simulated but realistic earthquake conditions. The Representa-

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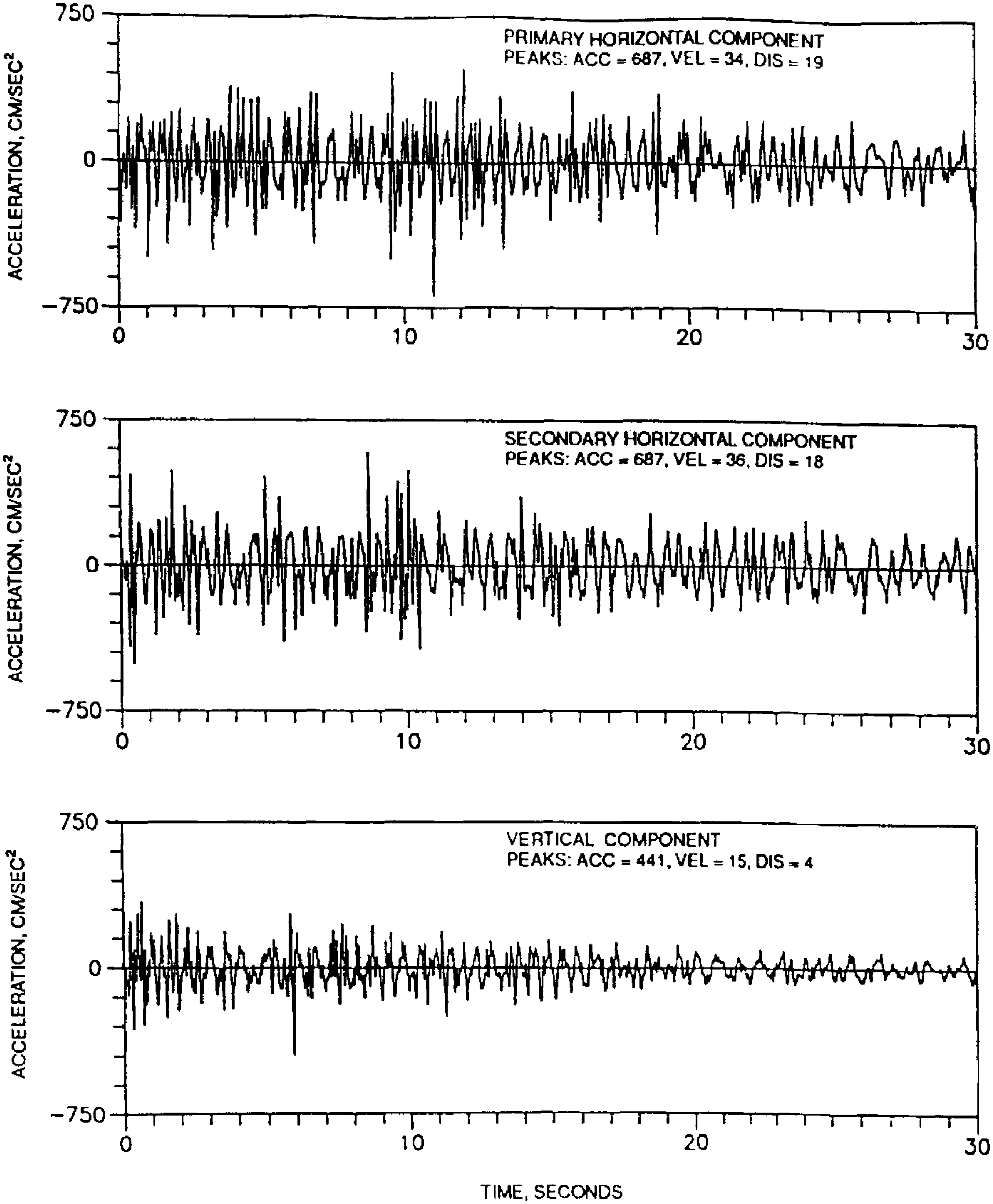

Figure 1 Representative Earthquake Accelerogram. This figure plots each of the three mutually perpendicular ground acceleration histories (acceleration vs. time) for the common 'Representative Earthquake' used in all analyses. Note that 981cm/s/s equal one 'g' unit of acceleration. This represents the very severe earthquake motion that would be experienced close to a large (magnitude 6.5+) earthquake.

tive Earthquake characteristics used in these studies (see Figure 1) were developed by Lindvall, Richter & Associates and are similar to the JPGM Design Earthquake Accelerogram [5].

The magnitude and often the type of response of an object are dependent on the characteristics of the earthquake accelerogram. The specific results given in this paper are based on the JPGM Representative Earthquake Accelerogram but the concepts and analytical procedures used are directly applicable to object/support systems at any location. Before applying the results presented here to other museum sites, a qualified earthquake engineer should be consulted to evaluate the potential, site-specific earthquake motion and to modify the results accordingly.

2 Modeling

Because of the unique character of art objects in terms of materials used, their distribution and degree of degradation, and the specific geometric configuration of the object, it was not possible to model each object individually. Instead, generic models representative of the major types of object/support systems were developed and specific museum objects were related to the generic models using appropriate parameters. These models, along with the anticipated earthquake response, are listed in Tables 1 and 2. The major difference between the two groups, Flexible and Rigid, in Table 1 is based on the definition that a rigid object—with respect to earthquake response—is one that will move without bending or flexing during low-frequency earthquake ground motion. An example of a rigid object is a marble bust, whereas a suspended painting or slender metal sculpture would exhibit a flexible response. As a consequence of resonance, the vibration amplitude of a flexible object or a flexible part of a mostly rigid object can be greater than that of the base or wall on which the object is supported.

Table 1 Generic object/support system models

Model name	*Earthquake responses*
Rigid	Rocking
Rigid	Sliding
Rigid	Stress, static
Flexible	2-D, swinging
Flexible	3-D, swinging
Flexible	Stress, dynamic

Table 2 Generic isolator models

Model name	*Description*
Isolator, friction	Low friction interface
Isolator, horizontal	Coulomb friction & viscous damping
Isolator, rotational	Damped oscillator

2.1 Rigid body rocking

The earthquake response of an unrestrained rigid object/support system consists of rocking (with possible overturning), sliding or, over time, some combination of these modes. Both rocking and sliding are complex, non-linear phenomena that have been studied for large, rectangular blocks but not for small, irregular objects. Ishiyama [6] proposed the following criteria for rocking and overturning of uniform rectangular objects: rocking will occur when the ratio of the maximum horizontal acceleration to the acceleration of gravity (g) (A_{max}/g), exceeds the ratio of base width (B) to height (H) of the object; and overturning of a slender rigid body will occur when the minimum velocity pulse (V) exceeds $10B/\sqrt{H}$. A simple method of extending these relations to arbitrarily shaped bodies with flat bases that are nearly symmetric about a vertical axis was developed in this study. The new relations are given by: $(A_{max}/g) > B/H'$ where $H' = 2h$ and (h) is the height to the centre of gravity (for rocking); and $(V_{max}) > 10B/\sqrt{H'}$ where V_{max} is the maximum pulse velocity. Thus, the rocking and overturning stability criteria are independent of friction coefficient, actual mass, and vertical excitation and are dependent only on object geometry, mass distribution, and the earthquake accelerogram.

Shown in Figure 2 is a diagram that defines the probable response of an object when subjected to the Representative Earthquake Accelerogram, as a function of B and H'. This diagram predicts that, for small objects with dimensions less then 20cm, overturning will occur immediately with no prior rocking. This behavior was confirmed experimentally using a shake table to simulate earthquake ground motion.

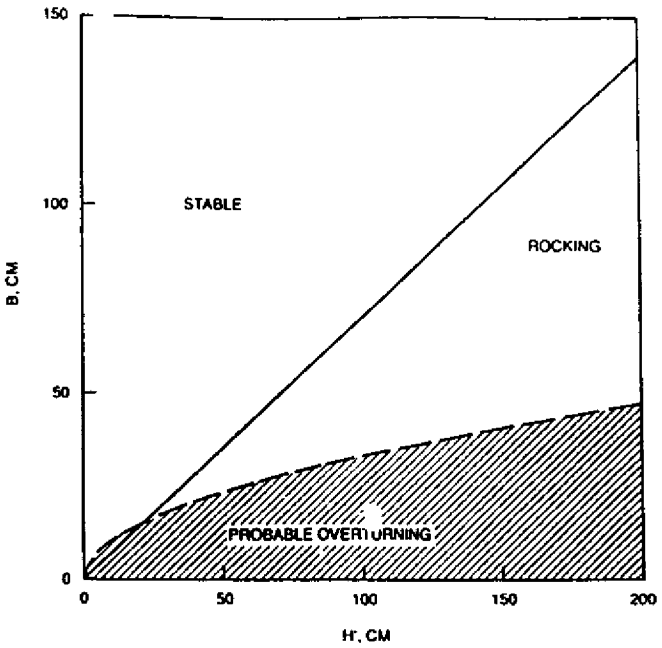

Figure 2 Rocking Stability Chart. This graph can be used to estimate the nature of rigid body rocking response for a given art object during the hypothetical worst-case Representative Earthquake. The vertical axis is the base width B; the horizontal axis is the equivalent height H'.

2.2 *Rigid body sliding*

Rocking response is usually not desirable and can be suppressed by rigidly fastening the object to its base. When this is not possible for appearance or structural dynamic loading reasons, it may be desirable to allow the object to slide freely during an earthquake, thus reducing the dynamic forces on the object. To avoid collison damage or a fall if the object reaches the edge of its base, the relative displacement response of a rigid object excited by the three translational components of the earthquake motion must be known. In this case, the friction coefficient between the object and the base must be known in addition to the A_{max}, B, and H.

The complex mathematical analysis of the motion of the object in response to the earthquake excitation was carried out and a computer program was written to implement numerical solutions to the motion equations. An example of the output for a given friction coefficient is shown in Figure 3. The line follows the time history of the relative path of the object during exposure to the Representative Earthquake. The most important result for each friction coefficient chosen is the maximum displacement

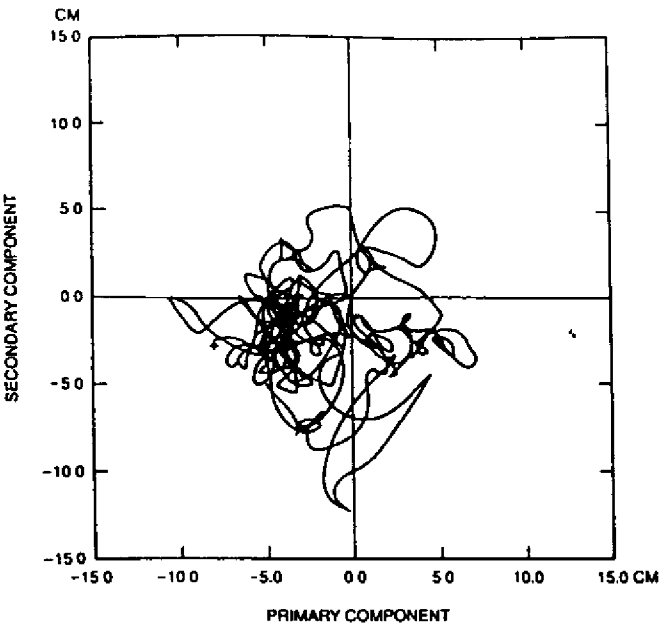

Figure 3 Polar Relative Displacement Response. This is a plot of the calculated sliding motion of an object with base friction coefficient equal to 0.05 during the hypothetical worst-case Representative Earthquake. The maximum radial displacement from start (0.0) is about 12cm.

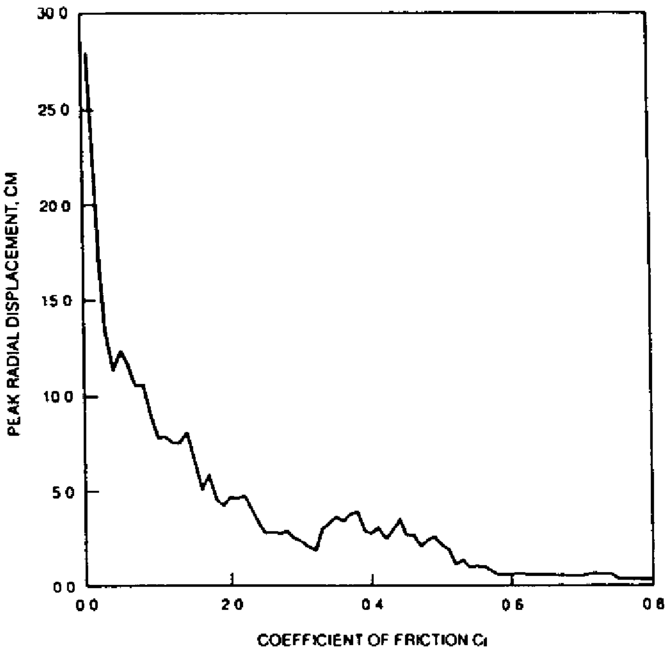

Figure 4 Maximum Sliding Displacement vs. Friction Coefficient. This is a plot of the maximum calculated radial displacement (see Figure 3) as a function of friction coefficient, C_f. These data can be used to estimate the mininum/horizontal separation needed to prevent sliding damage (from collision) during the Representative Earthquake.

Table 3 Suggested friction coefficients for use in maximum radial displacement estimation

Surface materials	*Suggested friction coefficient* C_f
Aluminum on terrazzo*	0.20
Marble on terrazzo*	0.15
Teflon® on terrazzo*	0.20
Aluminum on Formica®*	0.12
Marble on Formica®*	0.18
Teflon® on Formica®*	0.13
Aluminum on mosaic*	0.20
Marble on mosaic*	0.13
Teflon® on mosaic*	0.10
Aluminum on aluminum	0.24
Aluminum on plywood	0.37
Aluminum on coarse sandpaper	0.52
Aluminum on Teflon®	0.23

*Data from JPGM.

that occurs during the earthquake, a number that can be used as a guide for spacing objects that can slide so that collisions do not result. Figure 4 is a computer plot of the calculated maximum radial displacement versus friction coefficient for the Representative Earthquake. A knowledge of the approximate friction coefficient for an object/surface material combination will allow estimation of conservative, safe clearance distances between objects. Some experimentally determined friction coefficients are given in Table 3.

2.3 *Rigid body stress*

A rigid object/support system will not rock or slide if it is restrained at the base or other mounting points. In general, this is the safest mounting method for any object if the materials of which the object is constructed are strong enough to withstand the dynamic, earthquake-induced forces. A tall-stemmed glass object or a marble statue anchored only at the base may be too weak to withstand strong horizontal earthquake forces and may fracture, typically at the stem-base intersection or at the ankles of the statue.

Stress evaluation for a rigid body is based on equivalent static analysis using Newton's Second Law, $F=MA$ (force equals mass times acceleration). It can be seen that the maximum force will occur at the maximum or peak acceleration, A_{max}. Qualitatively, the horizontal force due to earthquake excitation can be simulated by tilting the object from the vertical and inducing the loading force by gravity. This force is equivalent to an earthquake acceleration of $g \sin \theta$, where g is the gravitational constant and θ is the tilt angle. Since the Representative Earthquake $A_{max}=0{\cdot}7g$, this corresponds to a tilt angle of 45°. Therefore, one can estimate the resistance to damage of a particular rigid, fixed base object/support system by asking the question: 'Would the object break if it were tilted 45° from the vertical?'.

More quantitative estimates of the stress resistance of objects can be calculated using basic statics and strength of materials principles [7]. The equivalent horizontal force can be considered to be concentrated at the center of gravity of the object. The most vulnerable part of the object occurs at a thin section that is located far from the center of gravity, for example, the ankles of a standing statue. Stress estimates should be made at this point and compared with the allowable or yield stress of the material. If the calculated stress exceeds the allowable, the object, in its present condition, is too weak to withstand the earthquake. Confidence in the results of this type of calculation depends on the accuracy with which the yield stress of the material from which the object was fabricated is known. Materials degradation, cracks, porosity, previous conservation treatments and other factors can result in overestimating the effective yield stress. Conservative estimates should always be used.

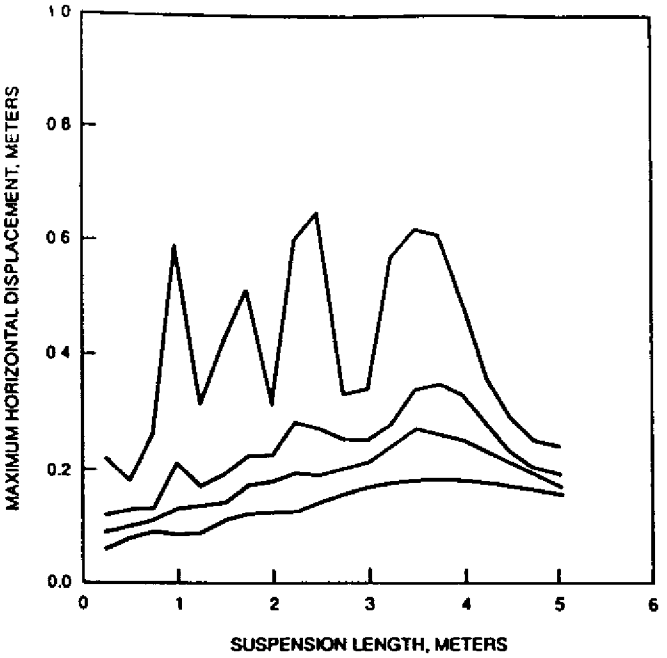

Figure 5 Hanging Painting Response Chart. A painting or other suspended object will move (swing) horizontally relative to the wall during an earthquake. In this graph, the calculated maximum horizontal displacement is shown as a function of suspension length for the Representative Earthquake. The four curves correspond to equivalent damping coefficients of 0.00, 0.05, 0.10 and 0.20 (from top to bottom).

2.4 *Flexible swinging response*

Suspending an object, such as a painting, is an effective means of reducing horizontal forces resulting from earthquake motion. This reduction, however, comes at the expense of potentially large pendulum displacements which could result in damaging collisions with walls or other objects. Therefore, it is necessary to be able to estimate horizontal displacements.

Simple pendulum models are valid only for small displacements and do not consider in-plane vertical excitation, resonant amplification, or energy loss by damping. Inclusion of viscous damping coefficient and in-plane vertical excitation terms in the simple pendulum model equation resulted in a differential equation that described the response of a two-dimensional (2-D) generic model. Figure 5 is a plot of maximum horizontal displacement versus suspension length for various values of the damping coefficient, C_V. Experimentally determined damping coefficients are given in Table 4. Out-of-plane responses (into and out of the wall) are difficult to model accurately, but their effects are expected to be random and fairly small and were therefore neglected in this analysis.

The generic 3-D swinging model can be used to represent objects, such as chandeliers, which are suspended from a single point in the ceiling. Again, large displacements are likely. The results shown in Figure 4 can be used to estimate maximum displacements in this case by setting $C_V=0$, taking the suspension length to be the distance to the center of gravity, and multiplying the estimated 2-D displacement by a factor of 1·4.

2.5 *Flexible system dynamic stress*

A flexible object/support system is one in which all or part of the system can respond to earthquake base excitation with greater motion than the base motion, that is, the earthquake motion can be amplified within the system. A slender metal sculpture will actually bend and the resulting stresses produced by earthquake excitation will be greater than if the system were rigid.

The generic model developed for rigid body stress analysis can be used here but the maximum acceleration (A_{max}) must be increased to account for this dynamic amplification. This was done by using a single-degree-of-freedom or simple harmonic oscillator model which requires a knowledge of the resonant frequency and damping coefficient of the flexible object. Methods for estimating these quantities and for calculating the new A_{max} were developed in this study. Use

Table 4 Experimentally determined damping coefficients for suspended paintings

Wall surface	*Painting surface*	*Damping coefficient, C_V*
Paint	Wood	0.02
Paint	Rubber pads	0.06
Cloth	Rubber pads	0.13

of these results allowed the estimation of maximum stress levels at suspected critical sections of an object.*

2.6 Base isolators

Earthquake base isolation is a relatively new research topic and in-depth studies go back only about 15 years. However, base isolation of higher frequency vibrations (rotating machinery) has been studied and applied for many decades. Earthquake base isolation builds upon the experience and theory of mechanical vibration isolation with special consideration given to the low frequencies and high displacements characteristic of the earthquake problem. Three types of base isolators that are in use or are being developed at JPGM were studied in this research: the friction isolator, an isolator that combines frictional and viscous damping, and a rotational, damped oscillator type of isolator.

The friction isolator is the simplest type and, by allowing sliding, will reduce transmission of horizontal earthquake forces to an object. A low friction coefficient material, such as Teflon®, can be inserted under an object to facilitate sliding and the displacement can be estimated by the method described earlier and from Figure 4. Prior to applying this type of isolation, the system must be checked for rocking stability because the friction coefficient is not included in rocking stability considerations. Reduction of the friction coefficient will not increase rocking stability of an object and any change in friction coefficient, such as that caused by an imperfection in the floor or a dirt particle, can change the effective friction coefficient and cause a sliding object to rock or possibly overturn during earthquake excitation. A trade-off exists between a reduction in transmitted acceleration and an increase in displacement. This is characteristic of all isolation systems and must be considered in the overall system design.

The horizontal base isolator acts by allowing limited relative motion between the object and the floor and usually contains a return system, which can be a spring or a gravity-based mechanical device. The return system allows the object to return to its original position after the earthquake and permits small static forces, such as those produced by human intervention, to be resisted. This type of isolator has been used at JPGM for large, heavy sculptures or for isolation of large display cases.

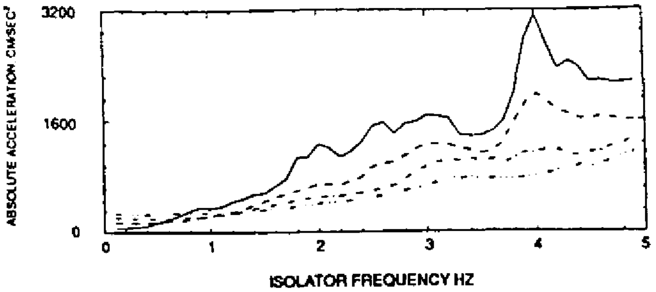

Figure 6 Horizontal Isolator Non-linear Response Spectrum. This chart is a design aid which shows how the acceleration of the isolated object varies with isolator resonant frequency (a design parameter). Maximum acceleration is a measure of isolator effectiveness. The viscous damping for this particular chart is 2% and the four curves correspond to friction coefficients of 0.05, 0.10, 0.15 and 0.20 (top to bottom).

The rotational base isolator is most useful for mounting objects that require restraint to prevent overturning yet cannot be clamped down rigidly at the base, owing to the possibility of failure at stress concentration points. The isolator is designed to allow rotation of the object but without vertical or horizontal translation. Typically, the isolator consists of an elastomeric pad (usually Sorbothane®, which is a polyurethane polymer) that is placed under the object, and a fastening system, which grips the object base on the inside and compresses the base into the elastomer. The pad acts as a torsional spring and returns the object to the vertical position. Such an isolator is very effective in reducing high local stresses which can occur at the corners of a fixed base object. The elastomer acts to distribute the forces along the entire base.

The three generic base isolation models were modeled analytically using linear and non-linear parametric equations. These equations were solved numerically to provide appropriate response parameters. Figure 6 shows a sample non-linear response spectrum for the generic horizontal base isolator, with friction coefficient

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*A detailed report on this study entitled 'Evaluation of seismic mitigation measures for art objects' has been issued and can be obtained by contacting the Conservation Research Program, The Getty Conservation Institute, 4503 Glencoe Avenue, Marina del Rey, CA 90292, USA.

as a parameter. Again, the calculation was made using the Representative Earthquake Accelerogram as input.

3 Experimental studies

Analytical modeling of even simple structural systems requires the use of approximations to fit the real system to the model. As the structural systems get more complex, these approximations can lead to large errors in the predicted behavior when compared with the actual behavior of the system. It was necessary, therefore, to verify experimentally even simple analytical models and the accompanying approximations prior to their application to a new class of structures.

Experimental studies were performed on rigid sliding and rocking models because the majority of object/support systems fall into these response categories and the corresponding analytical models were newly developed or extended from previous research and required verification. Experimental parameter approximation studies were performed for the swinging models and for the three types of generic base isolation models, both to verify the analytical models and to study model parameter approximations. No experimental studies were performed for the rigid and flexible stress models because the modeling was based on well-recognized linear methods. Where necessary, physical replicas corresponding to the generic art object/support systems were constructed. Actual base isolators or prototypes supplied by the JPGM were tested. Where possible, physical models had adjustable configurations and properties so that a range of generic model parameters could be tested.

To perform dynamic testing on object/support systems, two shake tables were designed and constructed. These were limited to 130 newtons (30lb force) maximum shaking force. Full-scale rocking stability tests on a full-scale 1780 newtons (400lb force) pedestal were performed on a larger shake table. All dynamic tests were single axis, horizontal excitation. Sine, swept sine, random and simulated earthquake excitation in the 1–20Hz range were used at various times. Specialized test fixtures were also built to study 2-D swinging, friction and damping constraints, and to study rotational isolators.

4 Discussion

To use the information developed in this study to analyze the seismic vulnerability of a specific object/support system, it is necessary first to define what is meant by failure for each type of model response. For rigid body rocking, failure is the onset of rocking, not overturning. The large forces generated by rocking impacts could damage susceptible objects and should be prevented from occurring. Sliding and swinging systems fail by impact with neighboring objects or walls and therefore relative displacement is the failure criterion. Stress resulting from base acceleration is the important parameter for both rigid and flexible stress models.

Another essential requirement is a definition of the design earthquake accelerogram at the museum location and, if possible, at the specific object location. Using this accelerogram, design criteria can be developed for each model using the analytical/experimental failure criteria. It must be emphasized again that the specific results reported here were based on the Representative Earthquake Accelerogram developed for the JPGM and that accelerograms for other locations may be different.

With these design criteria in hand, the evaluation of specific object/support systems can be attempted. The earthquake response category(s) is selected first, followed by the appropriate generic model. This will require some judgment and detailed knowledge of the condition and materials of the object and its support. It may be necessary to analyze the earthquake response using more than a single generic model. By insertion of the appropriate parameters in the model, the failure level of the object can be determined. If the object/support system is not adequate to withstand the postulated earthquake environment, strengthening, base isolation or removal from display should be carried out. The generic models can also be used to evaluate appropriate strengthening or isolation techniques.

5 Summary and conclusions

With the recent heightened interest in development of disaster mitigation plans for cultural property, the protection of art objects in museums located in seismically active zones has recently emerged as a problem of considerable concern. The research described in this paper was aimed at a study of this problem and was directed towards establishing a methodology for evaluation of the existing seismic stability of displayed objects. Generic object/support system models, both analytical and physical, have been developed for the most prevalent types of museum objects. Important parameters pertaining to the performance of the systems under earthquake excitation have been identified and techniques for estimating their magnitude have been suggested. Current and proposed methods to increase the earthquake resistance of objects in the J. Paul Getty Museum have been evaluated using state-of-the-art analytical and experimental techniques. This research provides a basic study of the problems involved in the protection from seismic damage of displayed museum objects.

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Résumé—On présente les méthodes d'évaluation de la limitation des dégâts causés par les tremblements de terre, utilisé ou à l'étude au Musée J. Paul Getty. On a modélisé différentes catégories d'objets et imaginé des méthodes analytiques pour permettre d'évaluer la susceptibilité des objets soumis à un balancement, un retournement, un glissement, à des endommagements sous contrainte, lorsqu'ils sont soumis aux forces d'un tremblement de terre. On discute les critères d'endommagement et on donne des exemples de méthodes mécaniques qui réduiraient la transmission des forces. Quelques unes des formulations analytiques ont été verifiées expérimentalement sur des modèles d'objets, en utilisant des ondes transverses ainsi que les accélérogrammes de secousses sismiques simulées à l'échelle de tables vibrantes de laboratoire. Les idées et procédés décrits sont généralement applicables aux autres musées et dépôts d'objets culturels.

Zusammenfassung—Der Beitrag diskutiert verschiedene Verfahren, die im J. Paul Getty Museum im Einsatz oder in der Entwichlung sind und die versuchen, die Folgen von Erdbeben zu mildern. Hierzu wurden für verschieden Objektklassen Modelle und technische Verfahren entwickelt. Diese erlauben eine Abschätzung, inwieweit sich Objekte während eines Erdbebens hin- und herbewegen, inwieweit sie umstürzen, rutschen oder unter der Belastung zerbrechen. Insbesondere letzteres wird an Hand von Beispielen diskutiert. Weiterhin werden mechanische Methoden zur Reduzierung der auftretenden Kräfte aufgezeigt. Einige der Überlegungen wurden an Objektmodellen auf Rütteltischen experimentell im Labor überprüft (mittels verschiedener, auch ein Erdbeben simulierender Anregungen). Die vorgestellten Überlegungen und Verfahren haben generelle Gültigkeit für andere Museen und Stätten kultureller Bedeutung.