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# Issues Related to the Selection of U.S. Navy Buildings for Base Isolation

*ABSTRACT* This report presents research conducted at UCLA. It recommends the base isolation systems that are fully satisfactory for Navy buildings. The report contains a discussion of the building selection process, quality control and design issues. A technical discussion of ground motion, torsion and uncertainty is also presented.



NAVAL CIVIL ENGINEERING LABORATORY PORT HUENEME, CALIFORNIA 93043

# METRIC CONVERSION FACTORS

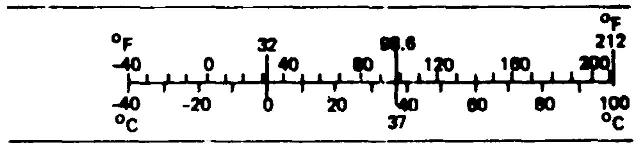
## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2,000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.


## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1,000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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This report presents research conducted at UCLA. It recommends the base isolation systems that are fully satisfactory for Navy buildings. The report contains a discussion of the building selection process, quality control and design issues. A technical discussion of ground motion, torsion and uncertainty is also presented.


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# FORWORD

This report describes research performed for the U.S. Navy, Naval Civil Engineering Laboratory, Port Hueneme, under the Seismic Hazard Mitigation Program (YM33F60001) . The research was performed under the direction of Mr. John Ferritto. The author wishes to acknowledge the assistance of Dr. Tom Sabol, and UCLA graduate students Won-Kee Hong and George T. Zorapapel.

## CONTENTS

# CHAPTER 1

## EXECUTIVE SUMMARY

Major structural engineering advances in the area of earthquake engineering have taken place with increased frequency since the 1971 San Fernando earthquake. Advances include (1) steel detailing for reinforced concrete buildings, (2) ductile design criteria for reinforced masonry shear walls and, (3) eccentric bracing of steel frames. One major advance has been the introduction of shock isolation concepts into building design and this advance is commonly referred to as Base Isolation. As with any new development, there are many proposed variations which more or less seek to satisfy the same objective. Some base isolation schemes are simple, well considered, and supported by both theoretical and dynamic experimental research. Others are not developed sufficiently to trust their use where U.S. Navy lives and operations are at risk.

This report presents the results of research conducted by the author and UCLA graduate students. It recommends the base isolation systems that are fully satisfactory for U.S. Navy buildings. It also addresses several key issues. Some of these issues are really "non-issues" and, at the present time, sufficient data exists to state that further research is not justified. Other issues do require further research to either greatly increase the quality of the final structure or to provide significant cost savings through uncertainty reduction.

The issues that are most often raised and that are really "non-issues" because they are sufficiently developed to provide acceptable structural engineering design confidence are:

(1) Description of design earthquake ground motion at the building site.

(2) Quality assurance testing of the base isolator components.

(3) Aging or replacement, if needed, of the base isolator units.

(4) Field construction and inspection.

(5) Architectural, mechanical and electrical interface.

The issues that are presently of concern have been divided into two categories. One category includes those concerns that must be resolved prior to U.S. Navy adoption of base isolation as a widespread and vailable option for Navy buildings. These issues are:

(1) Development of design criteria and commentary.

(2) Development of a position on second party independent review and field inspection.

The second category consists of those issues, in order of importance, that should be addressed in order to increase cost effectiveness and confidence in base isolation design.

(1) Research should be done to better understand the role vertical ground acceleration plays in base isolated building response.

(2) The real need for a back-up system needs to be rationally addressed to quantify the cost/risk reduction.

(3) The development of an expert system to facilitate its use by non-engineers such

as planners and architects.

(4) The development of an expert system to enable the U.S. Navy structural engineering staff to understand, review, and manage a base isolation project.

Research reports of this type always foster more issues that are worthy of discussion, and thus, further research. In this respect, base isolation is no different from steel, concrete or masonry building design. Issues such as torsional response and plan or vertical irregularity are examples. Although, we see the merit of these issues, they are not critical to total design confidence and no attempt is made herein to develop such a research agenda.

This report benefits from results published in a 1986 NSF workshop on Base Isolation that was presented by the Applied Technology Council [1.1]. Every effort will be made herein to present these research findings to our broader audience. To this end, Chapters 2 and 3 are intended to provide a foundation and also an identification of the factors that must be considered in the building selection process. Chapters 4 and 5 present the most commonly cited quality and technical issues. The author seeks to be specific while at the same time not overly detailed so as to not go beyond the interests of most readers of this report. Appendix A contains documentation of an expert system and is intended to illustrate the concepts of expert systems and not to address issues 3 and 4 above.

If the development of a design criteria and commentary and a position on second party independent review and field inspecion are resolved then base isolation will provide a viable economic alternative for many U.S. Navy buildings. Base isolation is a design advance whose time has arrived. It will be preferable for most hospitals and essential facilities.

# CHAPTER 2

# BASE ISOLATION

## 2.1 General

This section presents a brief introduction to the basic fundamentals of base isolation. The methods by which base isolation can be utilized are discussed as are the advantages and disadvantages of base isolation.

Figure 2.1 shows a schematic of the soil/isolator/building system. The isolator system provides an interface between the soil (foundation) and the building. Its function is to filter the input ground motion.

In the soil system of the base isolation model the relevant characteristics are the site soil properties, the potential for seismically induced settlement, instability, and liquefaction, and the nature of the ground motion input. In general, when base isolation is used, sites founded on moderately stiff to stiff soil will experience greater relative reductions to the input motion than will sites founded on softer, long period soils. Base isolation cannot mitigate the effects of settlement, slope instability, and liquefaction. The nature and magnitude of the input motion has an influence on the effectiveness of the base isolation system. The short period ground motion will be reduced to a greater degree by base isolation than will the long period ground motion.

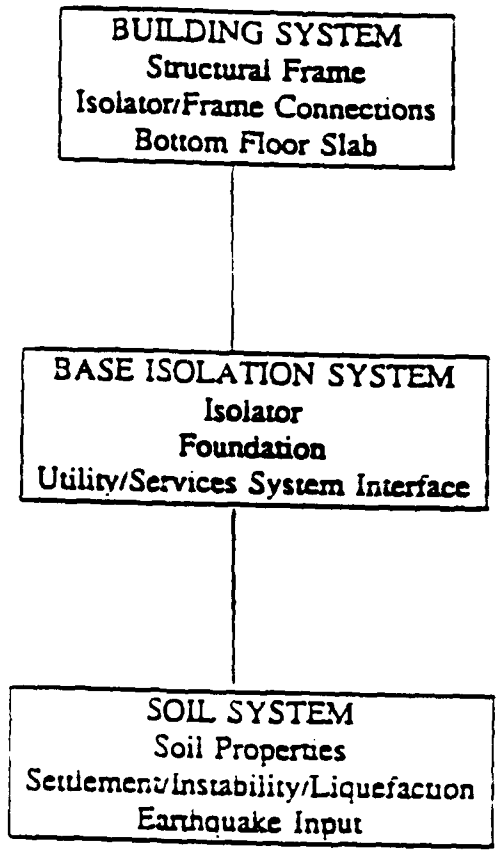



Figure 2.1 The Soil/Isolator/Building/System

The base isolation system consists of the isolators, foundation, and the interface between the site and building utilities. The bearing or other isolation elements act to modify the input motion transmitted through the foundation from the earthquake. Because of the motion generated by the base isolation system, an interface between the site and building utilities is required. These building utilities might be thought of as including the water, power, telephone, communication, sewer, and gas lines as well as the stairs and the elevator systems. Knowledge of the magnitude of the anticipated motion is required to accommodate this displacement and still permit the effected systems to function.

## 2.2 Concepts and Design Philosophy

Structural systems for U.S. Navy buildings are designed to resist seismic ground motion without collapse. Their Design Criteria for "typical" buildings provide for strength and ductility and prescribe seismic design forces which assume that the building's structural system will experience inelastic deformation and structural damage for major earthquakes that can typically be expected to occur approximately once every 75 to 100 years. The structural system is designed with structural details that provide sufficient ductility for the system to survive a major earthquake without collapse. This type of earthquake corresponds to an approximately once in 500 year event.

The inelastic deformations of a building's lateral force resisting structural system for the design earthquake will produce significant permanent structural damage to the members of the structural system. The associated interstory displacements will induce nonstructural damage to building components such as partitions, curtain walls, and glazing. Additionally, the dynamic response characteristics of the structural system will cause the earthquake ground motion to be amplified and the upper levels of the building will experience accelerations far greater in amplitude and duration than the earthquake ground motion imported to the structure at its base. These accelerations can cause significant nonstructural damage by inducing sliding or overturning of the contents of the structure, e.g., bookshelves, computers, electronic equipment, filing cabinets, and utilities.

## 2.3 Base Isolation System Response Characteristics

A base isolation structural system offers an alternative method of resisting seismic earthquake ground motions. The basic intent of most base isolation systems is to elongate the fundamental period of vibration of the total soil/isolator building system, and thus, reduce the earthquake induced accelerations at the floor levels. Figure 2.2 shows an idealized force response curve. By introducing flexibility at the base. for horizontal motion, the fundamental period of a building with a base isolation system is longer than the same structural system without isolators and is often beyond the range of periods that comprise strong earthquake ground motions. As a result, the magnitude of the accelerations transmitted to the superstructure above the base isolator system is greatly reduced. Stated differently, the base isolation system modifies the intense and damaging short period components of the ground motion and reduces the forces to the structural members. The system functions in much the same way as the shock absorber in a car. It filters out the short period or high frequency variations in the road surface.

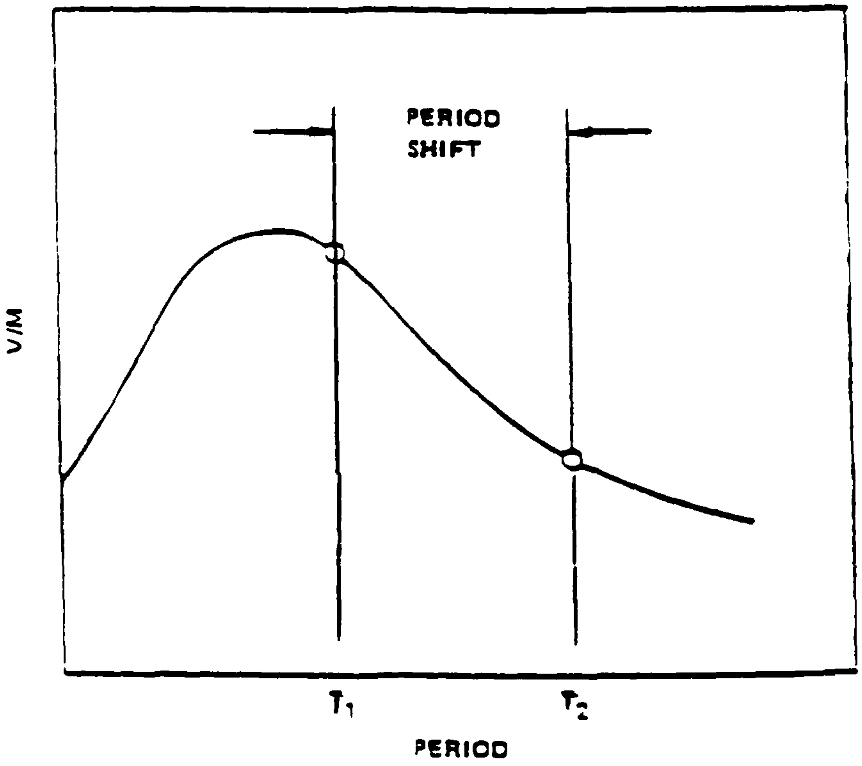



Figure 2.2 Idealized Force Response Curve

When a base isolation system is used the building floor accelerations are reduced but there is increased displacement in the system as a whole. The relative displacement between the floors of the building will decrease because the seismic forces imparted decrease but the total lateral floor displacements are large because the isolator displacement is large. The base isolator controls the response such that the isolators experience a large response (6" to 12") but the floor to floor displacements are small. The base isolation system must be designed to accommodate this deformation.

## 2.4 Base Isolation Systems

A wide variety of base isolation systems has been proposed by researchers. References 2.1 and 2.2 discuss these alternative systems. Table 2.1, which will be discussed later, provides an evaluation of these systems as they relate to U.S. Navy buildings. Currently, in the author's opinion, the only feasible base isolation structural system for a U.S. Navy building is one where the superstructure is supported on a set of elastomeric bearings that are located between the base of the superstructure and the building's foundation system. A typical schematic layout for such a base isolation structural system is shown in Figure 2.3. The bearings are located just below the basement level. Other locations are possible, for example at the bottom or top of a column. However, these locations require extra special care in both design and construction. Therefore, the following discussion applies to the situation shown in Figure 2.3

When developing the configuration of the base isolation system several factors having an impact on both structural and nonstructural elements must be considered. First, a floor

Table 2.1
COMPARISON OF BASE ISOLATION
AND ENERGY DISSIPATION SYSTEMS

| Trade Name | Restoring Force Capacity | Reserve Capacity and Structural Stability | Test Data | Resistance Aging | Tolerance to Imperfactions |
|---|---|---|---|---|---|
| Lead-Rubber Bearings | Yes. Energy dissipation sensitive to vertical load. | Can incorporate back-up safety system. Low displacements ensure good reserve capacity of 2 to 3 for P–Δ effects. | Large number of bearing tests. Three series of shake table tests. | Good for natural rubber with 20, 30 and 40 year data available. | Good |
| High Damping Rubber Bearings | Yes | Can incorporate back-up safety system. Larger displacements lower the reserve capacity for P–Δ effects. | Small number of bearing tests. One series of shake table tests in progress. | Compound recently developed. No long term data available. | Good |
| Damped Brace Frames | Yes | No backup system. Lower dispacements. | Component and shake table tests. | Reasonable but limited long term data available. | Fair |
| Rubber Bearings with Sliding Friction Plates | Partial but with permanent offset | Can incorporate back-up safety system. Reserve capacity ensured by sliding plate. | Many bearing tests. No shake table tests. | Neoprene can stiffen with age. OK if natural rubber is used. | Require very precise installation. |
| Earthquake Barrier System | Not in Current Design | Reserve capacity is function of limits on energy dissipating mechanisms. | No component tests. Shake table tests in progress. | Longevity of friction and ball bearing mechanism is unknown. | Require precise installation. |

Table 2.1 (Continued)
COMPARISON OF BASE ISOLATION
AND ENERGY DISSIPATION SYSTEMS

| Trade Name | Maturity and Number of Applications | Technical Support | Flexible Element | System Components Damping | Wind Restraint |
|---|---|---|---|---|---|
| Lead-Rubber Bearing | Installed in 2 Calif. bridges and over 30 structures in lower seismic zones. | DIS provides excellent support in U.S. | Elastomeric Bearings | Provided by Lead Plug Approx. 20 - 30% Viscous Damping. | Provided by Lead Plug |
| High Damping Rubber Bearings | Installed in 1 California building. | Limited availability in U.S. Malaysian Rubber Producers Assn. in England. | Elastomeric Bearings | Provided by rubber. Approx. 10% Viscous Damping. | Provided by Non-Linearity in Rubber |
| Damped Brace Frames | No current applications. | Available through private consultant arrangement and 3M. | None | Provided by friction or viscous device. Over 30% Viscous Damping. | Conventional System |
| Rubber Bearings with Sliding Friction Plate | No California installations. 4 Nuclear Plants in low seismic zones. | Available through U.S. agents for Electricite De France. | Elastomeric Bearings | Provided by friction of Sliding Plate and Rubber. | Sacrificial |
| Earthquake Barrier System | No Applications. | Available through M.S. Caspe. | Friction Surface or Ball Bearings | Provided by Control Beams, Friction Damper or other Mechanical Systems. | Provided by Control Beams or Friction Damper. |

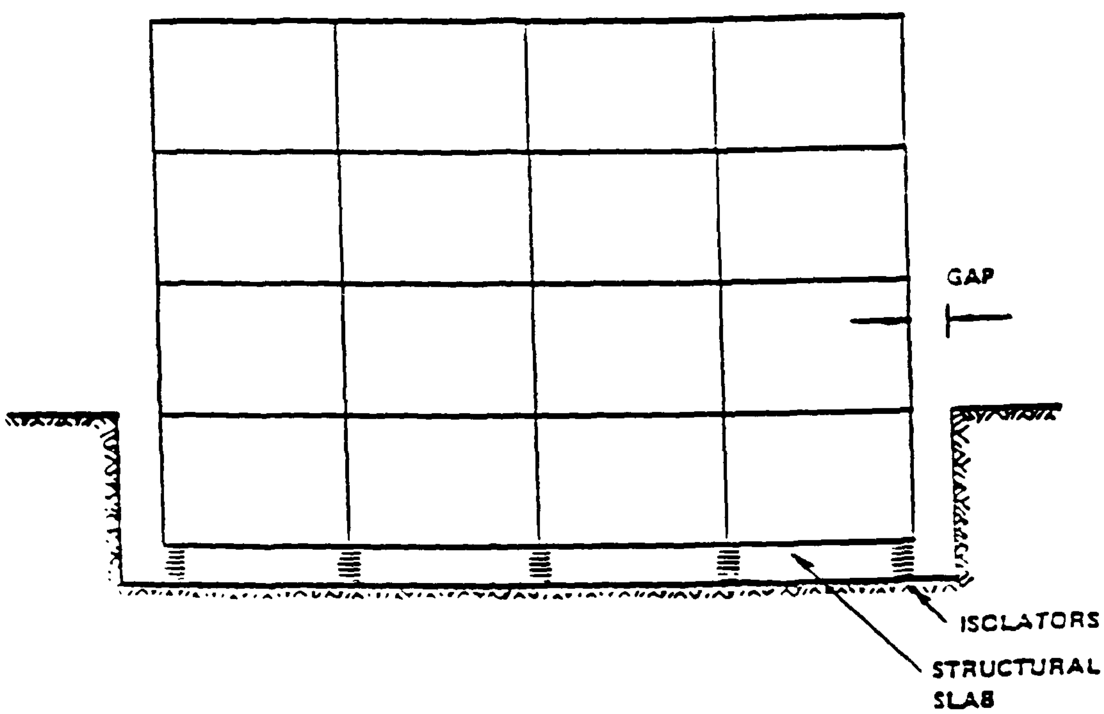



Figure 2.3 Typical Schematic Layout for Base Isolation

diaphragm at the base of the superstructure must exist to distribute the lateral forces from the superstructure to the bearings. Second, the bearings must be situated so as to be accessible for post-seismic inspection and, if necessary, replacement. Third, adequate horizontal clearance must be provided at the base level to accommodate, without serious expense, the large displacements in the base isolation bearings.

For the typical system shown in Figure 2.3, a separate perimeter retaining wall between the superstructure and the ground is required to provide the necessary seismic gap. Also, special consideration of such nonstructural elements as elevators and stairs as well as electrical, mechanical and utility lines is required. Flexible connections and special detailing are necessary to ensure continuity from the superstructure through the base isolator level to the exterior of the building.

The three types of bearings currently available for base isolation structural systems are:

(1) Reinforced elastomeric bearings.

(2) Reinforced elastomeric bearings with a lead plug damper.

(3) Reinforced elastomeric bearings with a friction slip surface.

All types of base isolators are a lamination of rubber and steel shim plates. The two materials are bonded together through a vulcanization process thereby developing a continuity such that the bearing will act as an integral unit.

The first base isolation bearing type is shown in Figure 2.4. It is a sandwich constructed of alternating layers of rubber and steel plates. Each bearing has a relatively low horizontal shear stiffness with the actual stiffness characteristics dependent on the dimensions

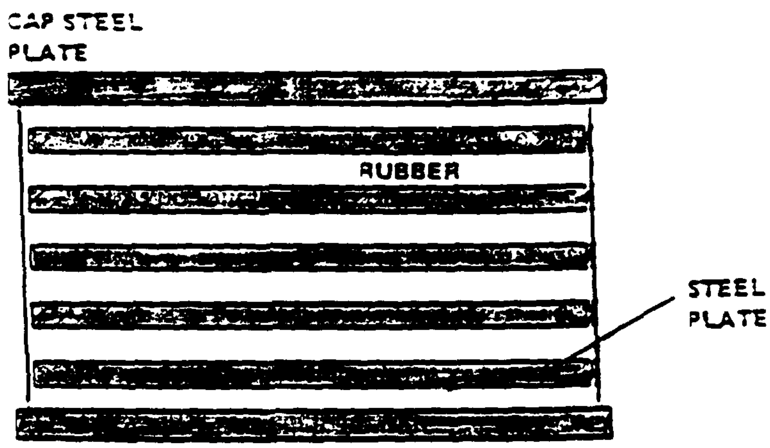



Figure 2.4 Elastomeric Bearing

of the bearing and the material properties of the rubber. It is desirable that the vertical stiffness of the bearing be as large as practical. By its nature, the bearing's rubber wants to bulge or "barrel out" (the Poisson effect) under any appreciable compressive load. Rigid steel plates are placed between layers of rubber and through their bond to the rubber the bulging is restrained. This provides vertical stiffness far greater than the rubber acting alone.

The bearing shown in Figure 2.4 has some inherent damping. To further increase the damping of the bearing, and thus, provide additional energy dissipation for the base isolation system two additional types of bearings have been developed. One type has a cylindrical lead plug placed in a preformed hole in the center of the bearing, see Figure 2.5. This bearing is essentially the same as the first type but the lead plug now provides increased damping through hysteretic energy dissipation. The rigid steel plates force the lead plug to experience plastic shear deformations that produce the desired hysteresis. In order for the lead plug to function properly a tight fit is imperative. The lead plug also functions as a stiffener under low level loads. The lead, having high elastic stiffness, provides rigidity against moderate wind or seismic loads.

The third type of bearing, shown in Figure 2.6, utilizes sliding friction to enchance its damping properties. The bearing is not rigidly connected to the superstructure and the interface between the superstructure and the bearing forms a friction surface. Hysteresis, and hence effective damping, is produced by the friction force developed between two plates sliding against each other. A design consideration for the system is the selection of an interface coefficient of friction that will restrain the superstructure under wind loads and moderate seismic excitations. At extreme seismic loads both the deformation in the bearing and the

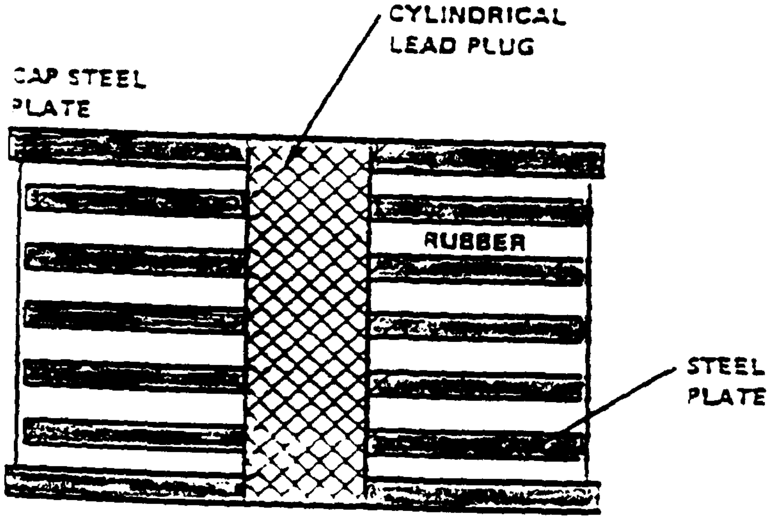



Figure 2.5 Elastomeric Bearing with Lead Plug

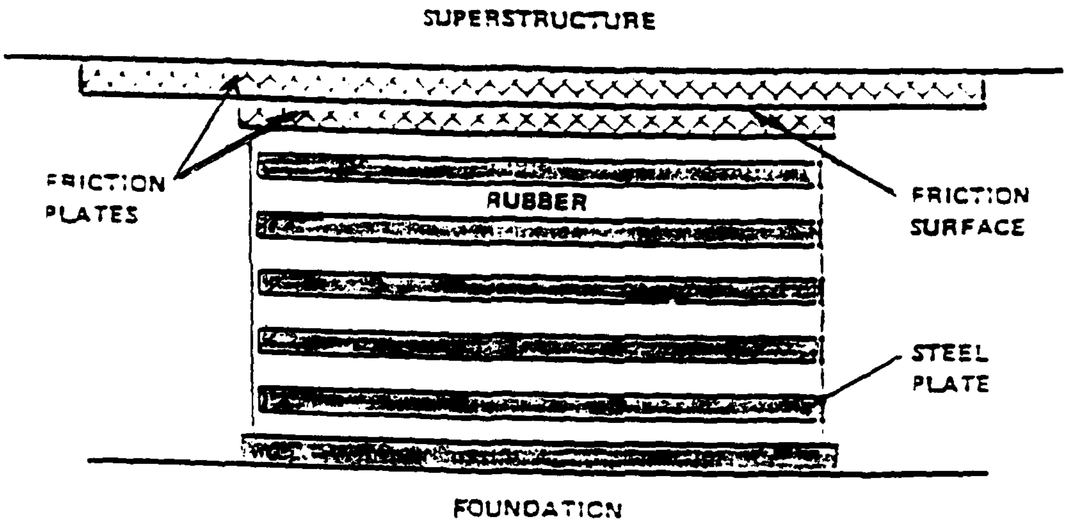



Figure 2.6 Elastomeric Bearing with Friction Slip Surface

frictional slip at the interface provide damping.

Other base isolation or other energy dissipation techniques to assist buildings in resisting earthquake shaking are currently receiving considerable structural engineering attention. Consider now some of the candidates this report has rejected.

Base isolation systems, as they are commonly understood in the United States, are primarily associated with elastomeric or rubber bearings being placed under each column of the building at the foundation level. However, a general definition of "base isolation" can also include other systems which include energy dissipation devices. These state-of-the-art devices provide earthquake energy dissipation through friction or viscous dampers typically added to the cross bracing members of the structure. Figure 2.7 shows an illustrative example of one type of energy dissipation system. This system uses a steel cross bracing energy dissipation system and was proposed by Pall. One advantage of the supplemental energy dissipation system of the type shown in Figure 2.7 is that it is typically added to the superstructure, and thus, no special consideration is required at the ground level such as building separation or flexible utility connections. Therefore, to call it base isolation is really stretching the definition. One usual drawback is that cross bracing may be architecturally restrictive. However, this system has undergone significant analytical scrutiny. A series of shaking table tests conducted by an internationally recognized and impartial expert in earthquake engineering at the University of British Columbia [2.3] has documented the system's reliability and effectiveness.

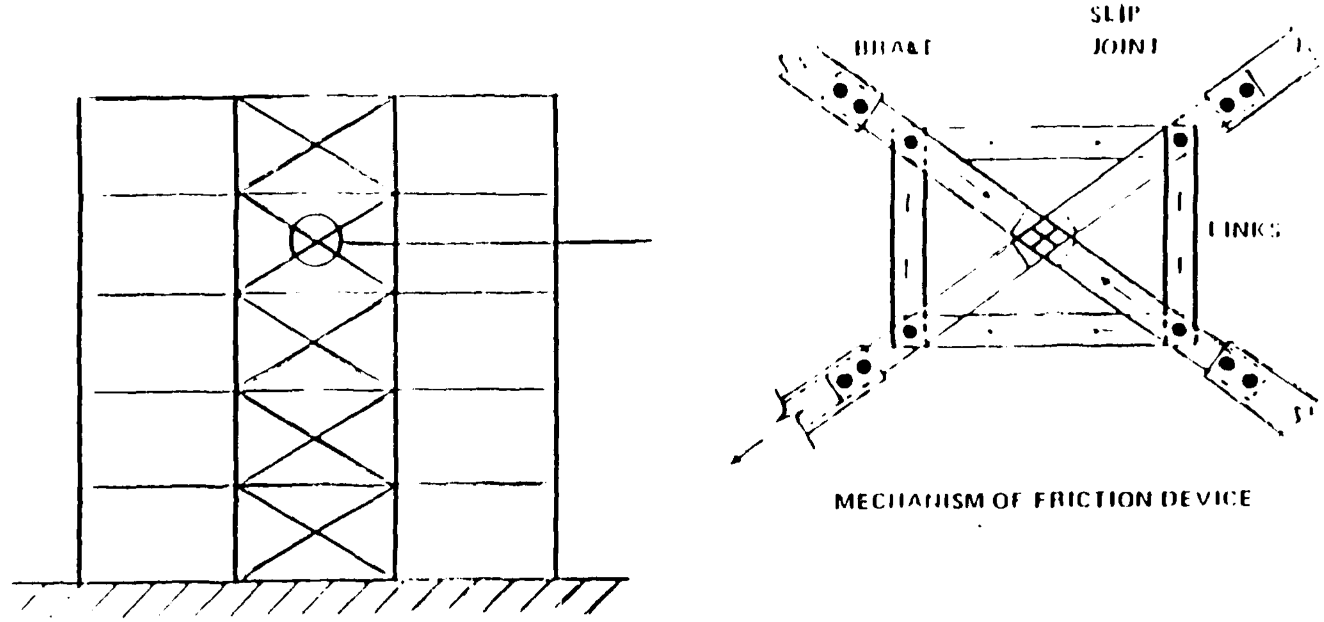



Figure 2.7 Building with Energy Dissipation Devices

Another system similar in concept utilizes viscoelastic damping devices in parallel with the cross braces. This device has been tested at 3M Laboratories and also by an impartial authority in earthquake engineering at the University of Michigan [2.2]. Good energy dissipation characteristics exist. These devices have been used successfully to damp out wind vibrations in the World Trade Center in New York City. Unfortunately, no shaking table tests have yet been conducted.

The Earthquake Barrier System has been developed by Mark S. Caspe [2.4]. The design is constantly being refined and consists of sliding teflon coated plates coupled with energy dissipating devices. The friction between the sliding surfaces is selected such that they slip after the earthquake force reaches a certain threshold level. However, at the present time and when compared with the other systems, we find little well documented analytical or experimental research has been conducted by impartial researchers.

The following three major factors were used in the evaluation process:

(1) **Technical**

Professional confidence must exist that the system selected will meet the technical requirements necessary to ensure proper function, predictability of behavior, and demonstrated long-term reliability.

(2) **Maturity**

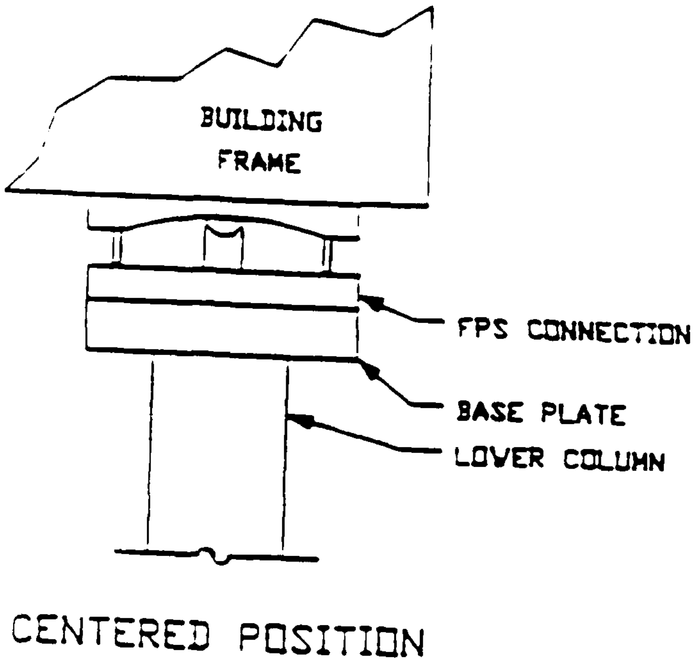
There must be significant maturity. Systems range from unused, untested concepts to systems that have been extensively tested and used for a significant number of structures. A mature data base of good quality experimental and analytical studies is essential.

(3) **Technical/Professional Support**

The construction industry relies on a network of engineers providing professional support to both promote their individual product and ensure its correct usage so as to enhance quality control. Therefore, the availability of technical/professional support for the system selected is very important.

Table 2.1 provides a summary of the systems reviewed in this research and comments on the evaluation factors.

A base isolation system which is of special note has recently been tested at UC Berkeley. Figures 2.8 through 2.10 show schematics of the system called the FPS Seismic Isolation System. The FPS (Friction Pendulum System) and the FPS connections are patented products developed by Earthquake Protection Systems, Inc., San Francisco, California that dissipate energy through pendulum action. Indications are that it is a promising system.



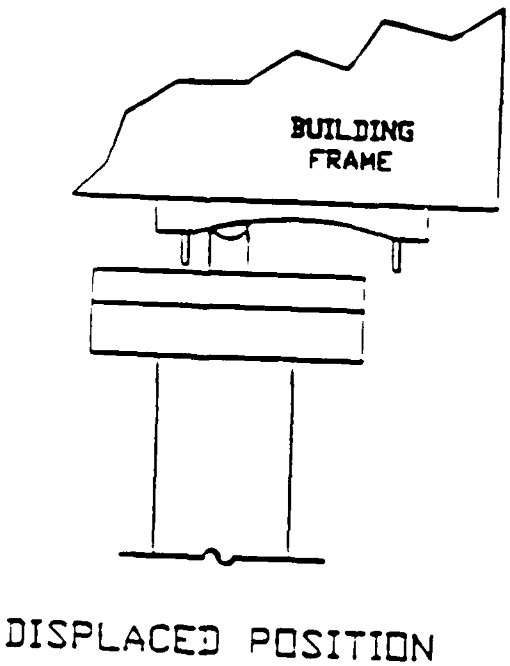




Figure 2.8 FPS Connection Operation

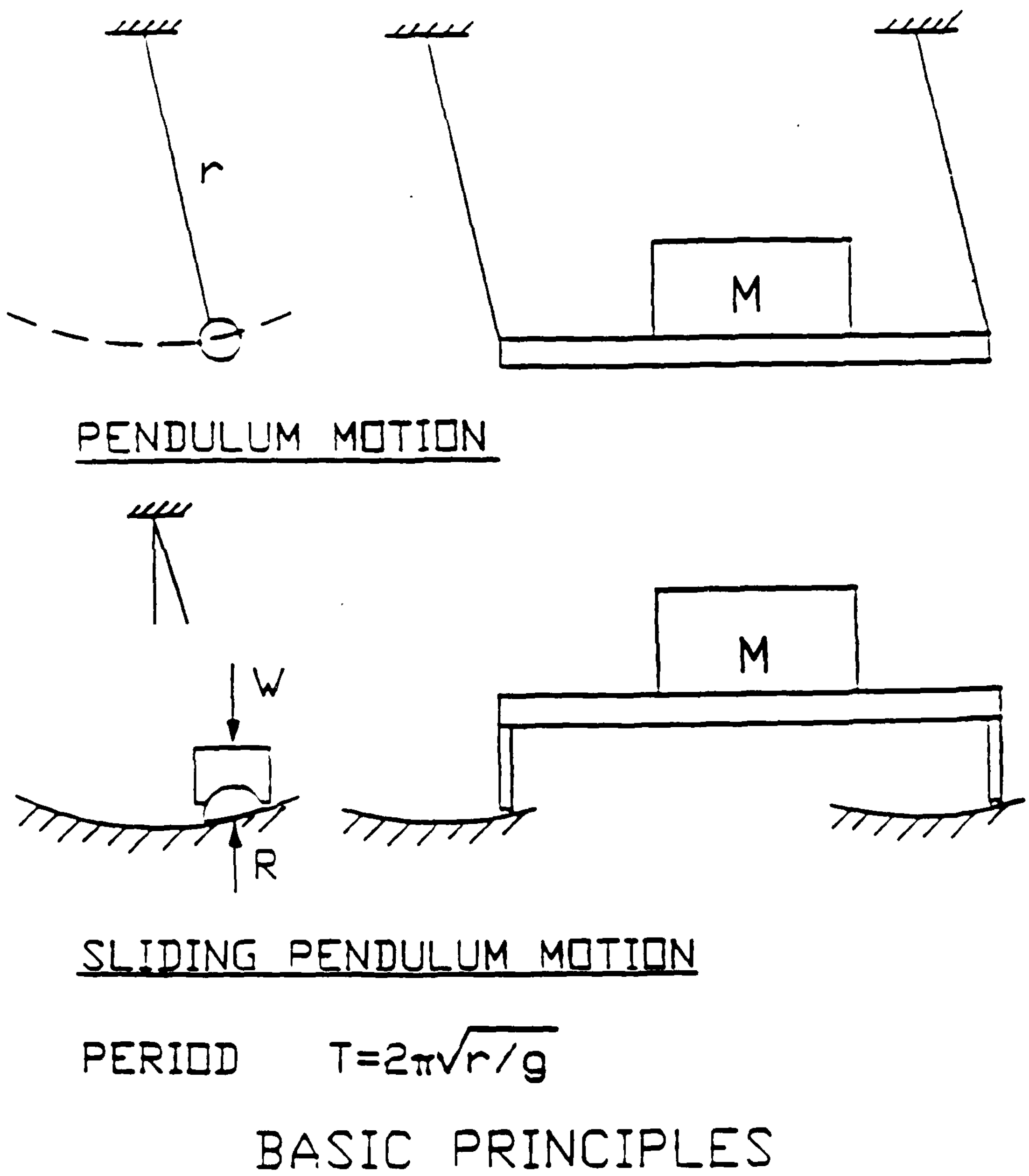



Figure 2.9 Friction Pendulum Concept

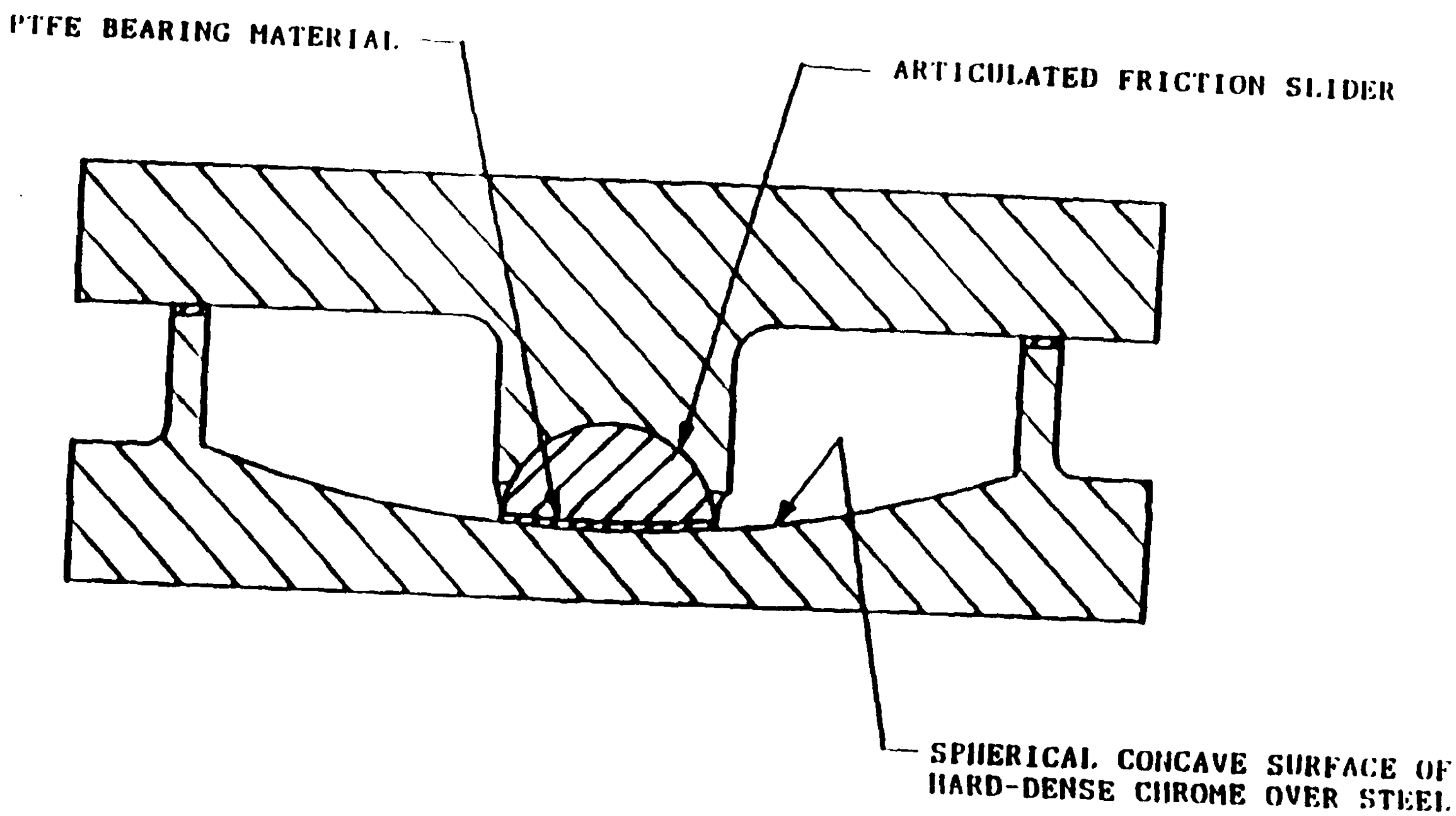



Figure 2.10 Section View of the FPS Connection

# CHAPTER 3

# BUILDING SELECTION PROCESS

## 3.1 General

Base isolation can offer many advantages over a conventionally designed building. The first step in the design process must be to see if such a system is a rational alternative for the specific building under consideration. A quantitative feasibility study can be performed at the very early stages of the design process that makes it possible to quickly determine whether or not base isolation is a feasible option. If such a study shows that a base isolation system is feasible, the 35% design phase should investigate relative costs and benefits between the isolated and non-isolated systems.

A feasibility study on a specific building must consider the following:

(1) The potential need for a base isolation structural system.

(2) The suitability of the site and the building.

(3) The cost effectiveness from a construction and a life cycle perspective.

## 3.2 Excellent Potential Applications of Base Isolation

Base isolation is most applicable for buildings located in areas of high seismicity where moderate earthquake ground motions (e.g. peak accelerations 0.2g or higher) are expected to occur every 15 to 20 years and where high design earthquake accelerations (e.g.

0.4g or higher) are expected to occur during the design life of the building. For conventional fixed base buildings, the U.S. Navy criteria assumes that minor structural damage will occur during a moderate earthquake. Such damage may not be deemed acceptable.

The intended use of the building is very important. Often, increased safety is required for mission essential buildings. For example, a U.S. Navy hospital is required to be operational both during and after an earthquake. Also, in many buildings, floor accelerations must be controlled to limit the overturning of computers or sensitive contents. Often, intrastory displacements must be limited to small amplitudes to minimize damage to nonstructural elements. These two factors, lowering accelerations and reducing strong drifts, work against each other in conventional structural systems.

### 3.3 Suitability of the Site

Short buildings having short fundamental periods of vibration without base isolation benefit the most, on a comparative basis, from base isolation. As a basic guideline, base isolation is best suited to relatively stiff, squat, low-to-medium-rise buildings in the range of 2 to 5 stories. These buildings have fixed-base fundamental periods of vibration that are typically less than 0.7-1.0 second. Because the isolators lengthen the period to 2.5 to 3.0 seconds this period shift typically reduces floor accelerations and forces by 60 to 80 percent.

The site soil conditions and geology are very important considerations in evaluating the suitability of a building for base isolation. In general, sites having moderately stiff to stiff subsurface soil are best suited for a base isolation system. The ground motion input applied at the structure's base is affected by the underlying solid deposit. Soft soils tend to filter out the high frequency motion of the seismic waves as well as provide some attenuation. As a result, soft soil provides a form of isolation itself. Therefore, we do not want to tune the base isolation system to the soil system. Sites with a site period greater than 1.0 second are not desirable. Stiff soils, on the other hand, transmit the high frequency motion. Therefore, by comparison, a base isolation system will be very effective for a building underlain by a stiff soil.

Finally, the candidate site must have adequate space to accommodate the predicted maximum horizontal displacements at the base. A base isolation system transmits lower forces but deflections across the isolators require clearances on the order of at least 6 to 12 inches.

### 3.4 Initial Construction Costs and Life Cycle Costs

The cost effectiveness of a base isolation system must consider the initial cost of the isolation system and the potential savings due to reduced damage to the building's structural system and contents over its design life.

The initial costs of implementing a base isolation system into a building design include the cost of the bearings and the associated structural and nonstructural factors required to accommodate the bearing system. Initial costs depend on the building and the extent of early planning. The costs usually include a rigid concrete slab above the isolators, bearings, a back-up system and the cost of providing a sufficient seismic gap around the building. Non-structural costs would correspond to the special detailing required for stairs, elevators and mechanical shafts at the isolator level. In addition, one needs special flexible utility connections.

The initial benefits are related to material quantity savings in the lateral force resisting system, reduction or elimination of sensitive equipment tie down costs, and reduced foundation costs. However, the most substantial benefits of base isolation are associated with life cycle costs. Structural damage arising from inelastic deformation in the superstructure can be expected to occur during the building's design life. However, nonstructural damage to a building's contents is related to floor accelerations which are significantly reduced with base isolation. Furthermore, base isolation decreases interstory drifts and associated damage to such nonstructural elements as cladding, glass and partitions without stiffening the building and increasing floor acceleration.

The initial construction costs for a conventional building are comprised of the following items.

(1) Structural costs such as structural steel, concrete or masonry.

(2) Non-structural costs such cladding, windows, partitions and fixtures.

(3) Machine, electrical, plumbing and vertical transportation system costs.

(4) General conditions (insurance, permits, inspections).

A base isolated building has additional costs associated with the cost of base isolators, or energy dissipation devices, the special detailing required at the isolation level to provide structural separation, and flexible utility connections.

Earthquake induced financial loss to a building can take many forms. The most direct loss is due to structural damage to the building's lateral force resisting system. Other forms of loss that can often equal or exceed structural damage are: (1) loss due to damage to non-structural contents such as computers and other equipment; (2) loss due to operational interruption; and (3) loss due to potential liability to occupants. Base isolation will have a positive impact on these costs.

Typical earthquake induced financial loss for commercial buildings is not relevant to or easily quantifiable for U.S. Navy buildings. For example, there are no insurance or financing costs for government buildings although there may be costs associated with alternative leasing arrangements used in lieu of constructing new facilities. The loss of "business" due to interr-uptions is not easily quantifiable because no direct revenue generating business is conducted such as is the case for commercial buildings. The loss of operational capabilities is certainly a clear consequence of significant earthquake damage. However, the costs associated with these problems cannot be clearly quantified.

Because of the uncertainties associated with predicting the maximum earthquake ground motion and the ensuing damage, an economic and performance evaluation of a base isolated building design versus a conventional building design must be addressed in a probabilistic manner. The potential methodology for this review is summarized in Figure 3.1. The components of this methodology are: (a) a probabilistic description of the earthquake damage, both structural and nonstructural, for a conventional and a base isolated building, (b) a probabilistic description of the anticipated earthquake ground motion, (c) an estimation of the initial cost of the building, (d) an estimation of the average annual earthquake loss based on (a), (b)

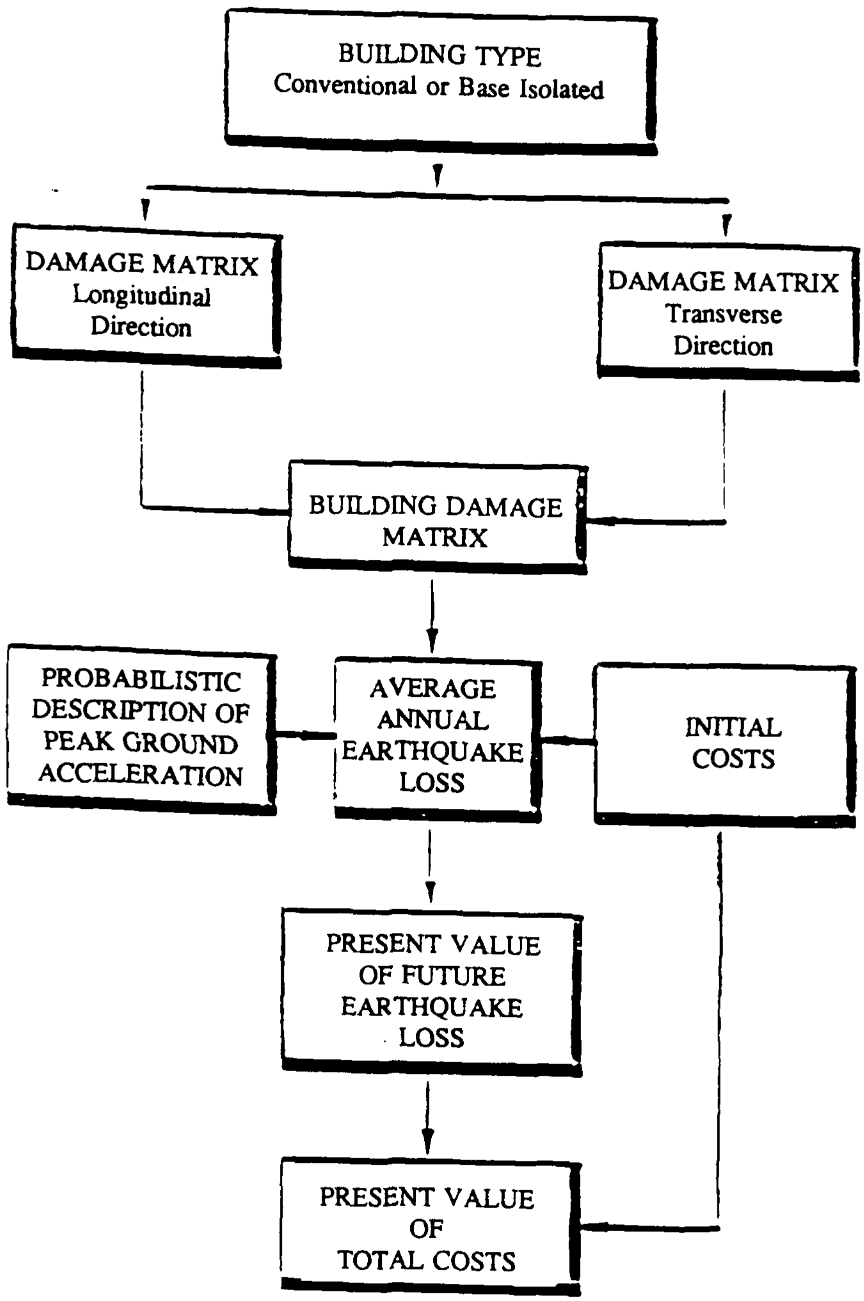



Figure 3.1 Schematic of Evaluation Methodology

and (c) above, (e) an estimation of the present value of future earthquake loss and, (f) the present value of total costs. The present value of the total costs so obtained for different structural systems can then provide the decision makers enough information to evaluate each particular structural system.

The damage matrix approach is appropriate for the feasibility evaluation of a base isolation system. This method of damage estimation was presented in a rudimentary form just after the 1971 San Fernando Valley Earthquake in a Massachusetts Institute of Technology study funded by the National Science Foundation. This approach has been extended and improved over the years using decision theory techniques plus our knowledge ot structural engineering.

### 3.5 Role of Expert Systems

A base isolation expert system is very desirable for effective technology transfer in the early planning stages of essential buildings. An expert system is a computer based system that can be constructed to play the role of human experts. These systems use specific questioning that enables users who are not structural engineers to describe their problems or goals. Eventually, solutions are provided through a process of inference.

A base isolation expert system will communicate with the user by providing information or definitions for the user who is not familiar with base isolation. The system explains why a question is relevant and it can explain or justify any solution or advice.

Six main components comprise a base isolation expert system. The components are: the input, output, user interface, inference engine, parser, and knowledge base. These components will now be briefly discussed.

(1) **The input** is provided by the user. It may be answers to the questions asked by the expert system or commands to the expert system.

(2) **The output** of the expert system takes the form of questions to the user in order to: obtain information, definitions or explanations when the user is confused; respond to commands from the user; or to provide useful information for the system user.

(3) **The user interface** transforms the contents of the base isolation/structural engineering knowledge base into a form that the non-structural engineer can comprehend. The most typical product of the user interface is the "menu" which prompts the user to obtain information for each variable contained in the knowledge base.

(4) **The inference engine** combines the user's answers to the questions posed by the user interface with the rules in the knowledge base in order to produce further questioning and, finally, the advice that the user needs. The inference engine also provides explanations that pertain to the advice given or the conclusions drawn.

(5) **The parser** is the interface between the author of the knowledge base and the

system. The author writes the components of the knowledge base in English like the rules used by a text editor. Then, the parser checks for mistakes and displays warnings to the author. If there are no mistakes, the parser translates the text into the format necessary for the knowledge base to be processed by the computer.

(6) **The knowledge base** is developed using published technical literature and existing U.S. Navy design information.

The users of a base isolation expert system will have a very limited knowledge of the problem. It is the role of the expert system to extract from them all the information concerning the environmental conditions of the problem and to explain the meaning or the purpose of the questions. There are 6 steps to the development of a meaningful base isolated expert system. These steps are:

**STEP 1. Identify Criteria:** The initial step is to clearly define the criteria used to evaluate the building for base isolation.

**STEP 2. Select an Expert System "Shell":** After identifying all the criteria, the size of the expert system must be estimated.

**STEP 3. Identify and Write the Attributes:** The attributes that receive their values from the responses of the user are called "input attributes". There are also "inferred attributes". Their values are computed by the expert system based on the rules in the knowledge base.

**STEP 4. Write the Logical Rules:** The rules show the expert system how to take the building description and derive the value of a certain inferred attribute from the values of the lower hierarchy's attributes. The complete set of rules is written after a flowchart of the problem is made that describes each move along the flowchart.

**STEP 5. Define and Write the Actions:** The base isolation expert system must be given directions to follow in order to reach the final conclusion. These directions are given in the form of "actions".

**STEP 6. Test the Expert System:** Like any other computer program, the base isolation expert system must be tested for different combinations of the values of its attributes in order to detect possible errors of judgment as well as to determine the program's usefulness.

For illustrative purposes, the draft entitled "Guidelines for Selection and Use of Base Isolation Systems" has been used to develop an expert system. The system was built to enable a nonstructural user (e.g. a design civil engineer) to perform a preliminary feasibility study for a building located in a certain seismic zone. Appendix A contains an illustrative example of a base isolation expert system.

# CHAPTER 4

# QUALITY CONTROL ISSUES

## 4.1 General

Quality control is an issue whose critical importance is obvious. Analytical model assumptions are only as good as the experimental data and professional insight on which they are based and the care with which the design is constructed. Quality control, for the purpose of this report, has been divided into three parts. First, it is essential to have good design criteria. Second, a quality insurance program for the isolators must exist. Third, field construction quality control must be addressed.

## 4.2 Design Criteria

The development of design criteria for base isolated buildings is not only possible but it can be done consistent with existing U.S. Navy Essential Building Criteria (TMS-810). The author took a very active role as co-chairman of a Structural Engineers Asociation of California (SEAOC) professional committee that developed base isolaton design criteria for California hospitals. It is clear that many areas of common agreement exist with the U.S. Navy Essential Building Design Criteria such as in quality assurance testing, the importance of torsion and near field displacements, etc. The SEOC hospital criteria is contained in Appendix B.

Base isolated structures differ in one major structural way from conventional buildings as they relate to EQ-I and EQ-II U.S. Navy criteria. The EQ-I performance criteria (typically a 50% chance of being exceeded in 50 years) for conventional mission essential buildings requires that the structural system remains essentially elastic with no steel member or reinforcing steel experiencing yielding. It is clear that base isolated buildings can have the same performance criteria for the structures above the isolators. However, the isolators themselves will experience inelastic deformation at earthquake excitement well below the EQ-I excitation. Therefore, the analytical model used to calculate the EQ-I response of a base isolated building must be inelastic whereas a model typically used for a conventional building is elastic. This difference creates a problem for structural engineers with little or no real understanding of structural dynamics. However, these individuals should not be designing base isolated buildings. The current problem is that a discussion does not exist as to an acceptable modeling approach followed by several illustrative examples. Technical manual TM 5-810 for the seismic design of essential buildings had to address just such a technical issue. It accomplished this beautifully in both its discussion and examples for Post-Yield Analysis Provisions (Section 4-4, pg 4-7). The same approach can and should be used for base isolation.

The EQ-II performance criteria (typically a 10% chance of being exceeded in 50 years) for a base isolated mission essential building should be the same as for a conventional mission essential building. No reason exists to modify the concept that a post-yielded analysis is necessary and that inelastic demands should be less than pre-established values. What is not appropriate is to use the capacity spectrum method at the exclusion of multiple strong motion time history analyses. Inelastic strong motion time history computer codes for building design are today variable and affordable (e.g. DRAIN-2D, NOODY).

A U.S. Navy design criteria that is consistent with the philosophy of the U.S. Navy Mission Essential Building Criteria and the SEAOC hospital criteria is needed for base isolated buildings. The existance of such a criteria will improve the quality of design. This improvement will be most evident in less designer and structural review confusion.

## 4.3 Quality Assurance Testing

A detailed study of the SEAOC hospital criteria in Appendix B will clearly indicate that quality assurance testing was a major SEAOC concern. It was also a task that could be addressed by committee and it has, in the author's opinion, been solved by SEAOC. What is needed is a review and then some possible modification to address any special needs of the U.S. Navy. For illustration, some issues that have been addressed are:

(1) The nature of cyclic time history loading on isolation.

(2) The minimum acceptable base isolation displacement capacity.

(3) The number of isolators tested.

Performance specifications have been developed by SEAOC, and thus, any propriety issues do not exist.

## 4.4 Field Construction Quality Control

Existing U.S. Navy procedures are essentially acceptable for base isolated buildings. Experience indicates that base isolated designs can be less complicated to construct and easier to inspect than conventional buildings. By virtue of the reduced seismic loads we can expect to have less ductile moment connections and less reinforcing steel congesting small areas.

One item of special note is that the structural engineer of record should be contracted to provide regular job site visits for the purpose of observation. This is currently done with some conventional building projects but it should be required on all base isolated building projects. Placement of the isolators is critical and the load paths for the building must be inspected.

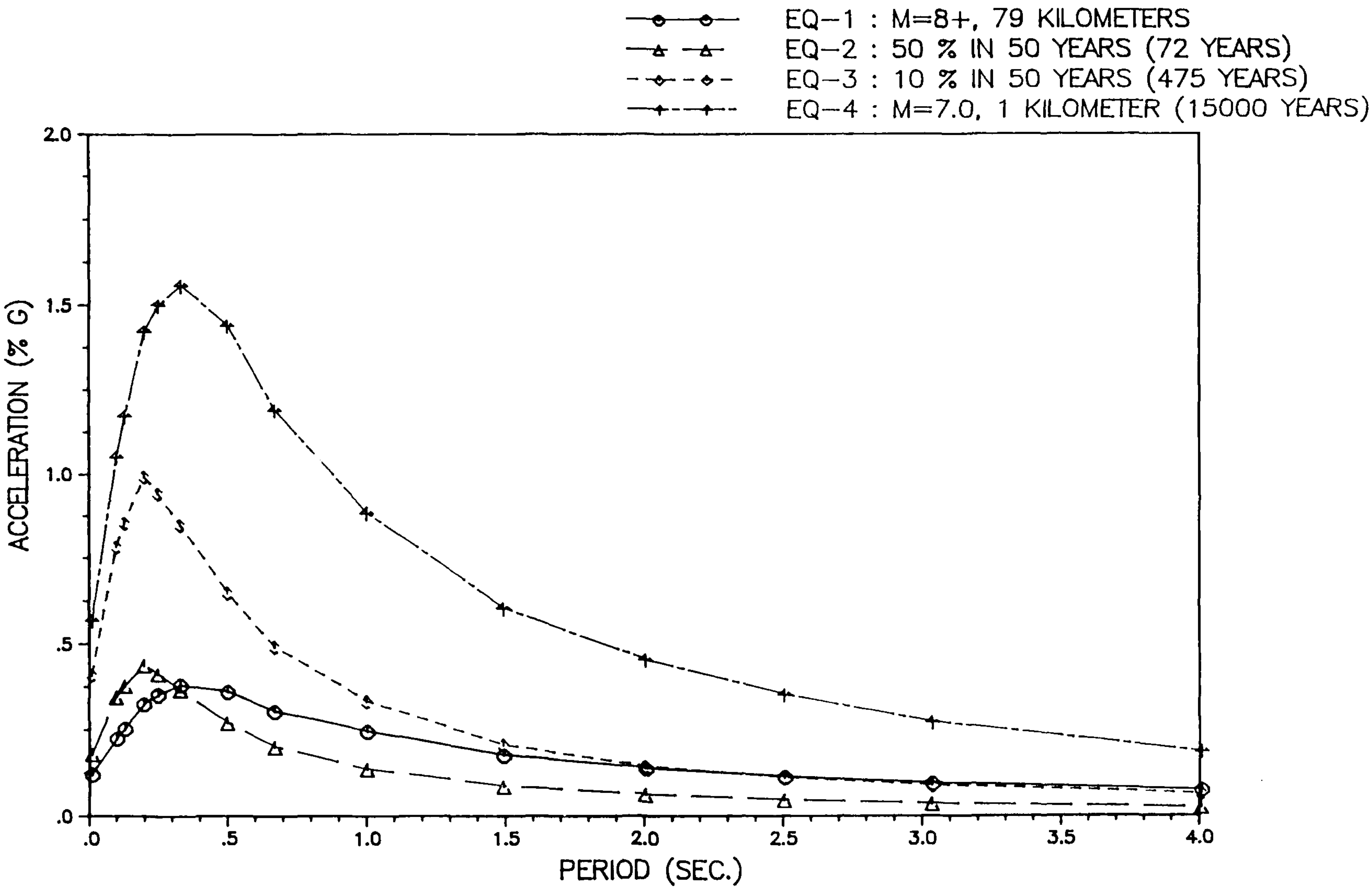



Figure 5.1 Response Spectra

# CHAPTER 5

# TECHNICAL ISSUES

## 5.1 General

This chapter provides insight into several technical issues. The approach taken is to identify those technical issues that should be discussed because of concerns expressed by others or a desire to highlight the need for a more in-depth study of particular issues.

## 5.2 Local Fault Ground Motion Excitation

The design criteria for base isolation must require the development of site specific ground motion histories and response spectra. It is clear from Figure 5.1 that a design spectrum can be exceeded by smaller local fault generated earthquakes. With a geotechnical study of the site the topic of local faults and near field ground displacements will have been addressed and the issue becomes a non-issue.

A real concern and perhaps a secondary issue is that the A/E selection process must provide a detailed review of the geotechnical consultant. This is not typically done when the leader of the U.S. Navy interview team is an architect rather than a structural engineer. However, this is an administrative issue which can be resolved by others.

A pool of qualified geotechnical consultants exists who can rationally estimate field as well as far field design earthquake ground motions. Therefore, the selection of a qualified consultant is not an issue.

## 5.3 Dynamic Analysis of Buildings

Prior to 1970 most structural engineers were not educated in even the basics of structural dynamics. Today, most structural engineers know at least the basics and understand response spectra analyses. Therefore, it's reasonable to take the position that for a "high tech" system such as base isolation structural dynamics must be used.

The SEAOC hospital criteria requires a dynamic analysis. The U.S. Navy should have a similar requirement.

The U.S. Navy Essential Buildings Criteria has two levels of performance which are addressed as EQ-I and EQ-II design. It is the position of this research that:

(1) The EQ-I earthquake motion be prescribed in terms of either a response spectra or a set of time histories. This choice can be made by the structural engineer of record. The resulting analysis can be a dynamic analysis with an equivalent linear elastic spring representing the isolator.

(2) The EQ-II earthquake motion shall be a set of time histories. A step-by-step dynamic analysis is required.

## 5.4 Torsion

Torsion is not really an issue but it is a topic raised over and over again. The current design criteria for ordinary U.S. Navy buildings does not require a three-dimensional dynamic analysis. However, a base isolated building should have such an analysis. If this is done, torsion is accounted for in the design.

Accidental torsion, however, is a topic requiring comment. No technical basis exists for the current criteria for accidental eccentricity. If no criteria exists the data available to technically support the 5% number does not exist. However, like many items in the design criteria, it is a requirement that has served its purpose. If the issue is how do we model structural system torsion then it is not an issue. If the issue is how do we model construction errors, the three dimensional twisting of the ground, etc, then research needs to be funded by the U.S. Navy on this topic.

### 5.5 Back-Up System

The research conducted as part of this project involved talking with many, many structural engineers about back-up systems. Items discussed were the need for the system and the type of system to be used. This is a real issue and a very expensive one.

A back-up system can cost, at minimum, several hundred thousand dollars. It is intended to provide a secondary line of safety if the isolation components fail. The intent is good but the benefit and cost/benefit is unclear. The arguments, at this time, are emotional.

Research does not exist to clearly document the technical benefits of a base isolation back-up system. If the isolators do fail and if the back-up system comes into action then the theory of structural dynamics must be used to quantify the resultant response, not speculation.

Such studies have not been done to the author's satisfaction, and therefore, this issue is viewed as a top priority that can be technically solved with a reasonable amount of research effort.

## 5.6 Vertical Ground Motion

This issue transcends base isolated buildings and really applies to all buildings. Sufficient data exists to address the impact of vertical ground motion on the dynamic response of a base isolated building on a building by building basis. However, the level of effort is large and the cost is probably best not handled on a project by project basis.

A detailed analysis of one or more case study projects is recommended using site specific time histories of ground motion input. This type of a research effort would provide insight and probably an answer to the question - Is it time to let our structural dynamic models include vertical ground motion input.

## 5.7 Soil Uncertainty Input

This is a very interesting issue because early returns are that the inclusion of isolators between the soil and the structure may significantly reduce the uncertainty in the soil/building system. The isolators act to filter out some of the uncertainty associated with soil modeling and parameter values.

Models of the soil/isolator/building system have been done using elastic half space models and, as part of this research, simple spring mass models. The results are inconclusive because the scope of study has been very liimited. Finite element models could similarly be developed for the system. Research should be carried out on this topic but in order to develop reliable design guidelines considerable effort wll be required. Therefore, the research is probably best accomplished over a two to three year span of time. The research must include the nonlinear response characteristics of the soil.

# CHAPTER 6

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# APPENDIX A

# ILLUSTRATIVE BASE ISOLATION EXPERT SYSTEM

## A.1 What is an Expert System?

Expert systems are computer based systems that can be constructed to play the role of human experts. These systems use specific questioning that enables users to describe their problems or goals completely. The user input is processed according to the rules provided within the knowledge basis of the expert system. For each specific problem further questioning is directed. Eventually, solutions or advice are provided through a process of inference.

Expert systems seek to communicate clearly with the user. They are able to provide additional information or definitions in cases where the user is not familiar with the items related to the content of a particular question. The systems can also explain why a particular question is relevant in case the user is confused. Eventually, the systems can explain or justify any solution or advice.

Expert systems can solve problems in any possible domain, ranging from business to education to government. They can find specific information and give advice on how to use this information. They can be utilized to provide the expertise of an employee who is absent, leaving or retiring. They can save the time of a highly qualified employee, transferring complex problems to a regular employee who usually performs routine work. The ability of expert systems to explain their conclusions is valuable for customer relations as well as for staff training.

A more sophisticated and rewarding use of expert systems is related to their feedback. Suppose that criteria and the rules for practical application have been set for a new product or activity. Instead of costly and sometimes painful experimental application, a simulation process can be used to explore the possible consequences of the new criteria. The most appropriate tool to perform the simulation would be expert system whose knowledge base contains the new criteria and the rules. This expert system can be given to several users who will try different possible situations. Eventually, the solutions and advice provided by the expert system will be reviewed, possibly along with their justification, from the viewpoint of feasibility and possible implications. If all the results look reasonable, the set of rules can be validated. If unacceptable consequences are found, the justification logical path will point to rules for their consideration.

Three categories of individuals must be involved in creating an expert system:

(1) The domain expert is the source of information for the knowledge base. Sometimes, his, or her expertise is already organized in books, articles or other types of documents.

(2) The knowledge base author organizes the information from the domain expert and writes the "English-like" knowledge base.

(3) The knowledge engineer is a computer scientist who writes a program that generates the expert system starting from the "English-like" knowledge base written by the knowledge base author.

The users of the expert system may have only a very limited knowledge of the problem or the goal to be reached. It is the role of the expert system to extract from them all the information concerning the environmental conditions of the problem and to explain the meaning or the purpose of the questions.

Presently, there are several programs on the market that are able to generate expert systems. They differ mostly by the size of the knowledge base. There are several measures of the capacity of a knowledge base. In our opinion, the most significant feature is the number of rules the knowledge base can support because this is the limitation that is most often encountered in practical applications. Programs for illustrative or educational purposes usually have twenty or thirty rules as their capacity limit. However, programs that can support a knowledge base that contains up to 2000 rules and yet can be run on microcomputers are already on the market. structures. The "field of experience" becomes an attribute.

### A.2 Illustrative Sample

For illustrative purposes, the draft entitled "Guidelines for Selection and Use of Base Isolation Systems" has been used as the expert document. An expert system has been built in order to enable a common user (ex. a civil engineer) to explore the possibility of using the base isolation solution for a building located in a certain seismic zone.

### STEP 1. Identification of Criteria

1. Seismic zone criterion: base isolation solution can be considered for seismic zones 3 and 4. In case of special structures the solution can be considered also for zone 2.

2. Soil type criterion: the structure must be located on firm soil or rock.

3. Variability in soil conditions: variations in conditions across the site are undesirable.

4. Liquefaction potential criterion: the areas of potential liquefaction should be avoided.

5. Near field criterion: base isolation should not be used for structures located within 2 miles of an active fault (probable considering the danger of the long period pulse due to the Doppler effect).

6. Configuration criterion: for existing structures presenting irregular in plan configurations like "H", "L", "E", and others, the base isolation rehabilitation solution is not allowed. For new structures, the solution becomes possible only when providing appropriately located seismic joints. This additional requirement must be considered in the cost analysis.

7. Natural period criterion: an upper limit of 0.7 seconds (for the structure considered without isolators) will be established.

8. Cost of the base isolation solution: this criterion has been added to the initial set in order to provide a final trial step before reaching the conclusion. For illustrative purposes, three ranges of cost per square foot have been considered so far. If the base isolation solution has "passed" the preceding criteria, this last comparison will complete the screening process. If the cost is in the "ball park" a more detailed analysis is recommended; for lower or higher costs, the recommendation of adopting or discarding the base isolation solution is given.

## STEP 2. Selection of an Expert System Shell

The program used for this example is MICRO PS. It is available from Ashton-Tate as part of an expert system book/computer program package entitled Building Your First Expert System by Nagy, Gault and Nagy.

## STEP 3. Identify and Write the Attributes

| Attribute | Values |
|---|---|
| 1. Seismic zone | 1<br>2<br>3<br>4 |
| 2. Special structure | yes<br>no |
| 3. Soil type | soft<br>firm<br>rock |
| 4. Liquefaction potential | low<br>moderate<br>high |
| 5. Variable soil conditions across the site | yes<br>no |
| 6. Smallest distance to an active fault | less than 2 miles<br>more than two miles |
| 7. Building status | existing<br>new |
| 8. Shape in plan | square/rectangular/circular<br>other |
| 9. Structural system | steel frame<br>reinforced concrete frame<br>shear wall system |

| | |
|---|---|
| 10. Building height range | less than 35 feet<br>35 feet to 67 feet<br>67 feet to 100 feet<br>more than 100 feet |
| 11. Building depth range | less than 50 feet<br>more than 50 feet |
| 12. Cost of base isolation solution | less than 15 $/sf.<br>15 $/sf. - 30 $/sf.<br>more than 30 $/sf. |

**STEP 4. Write the Logical Rules** (See the following pages for the rules.)

NOTE: The data file for this example of the MICRO PS computer program is available from the author upon presentation of the purchase receipt for MICRO PS.

attributes:
seismic zone
(int): from 1 to 4.
special structure
(smlt): yes,no.
soil type
(smlt): soft soil,firm soil,rock.
liquefaction potential
(smlt): low,moderate,high.
variable soil conditions across the site
(smlt): yes,no.
smallest distance tu an active fault
(smlt): less thann two miles,more thann two miles.
building status
(smlt): existing,new.
shape in plan
(smlt): square or rectangular or circular,other.
structural system
(smlt): steel frame,reinforced concrete frame,shear wall system.
building height range
(smlt): less thann thirty five feet,between thirty five and sixty seven feet,between sixty seven and hundred feet,
more thann hundred feet.
building depth range
(smlt):less thann fifty feet,more thann fifty feet.
cost of base isolation solution
(smlt): less thann fifteen dollars per square foot,between fifteen and thirty dollars
per square foot,more thann thirty dollars per square foot.
path1
(smlt):ok,ng.
path2
(smlt):ok,ng.
path3
(smlt):ok,ng.
decision
(smlt): the base isolation solution is recommended,more detailed analysis is requested,
the base isolation solution is not recommended
%
rules:
r1

```
        if seismic zone = 1,
                /soil type = soft soil,
                /liquefaction potential = high,
                /variable soil conditions across the site = yes,
                /smallest distance tu an active fault = less thann two
                miles,
        then path1 = ng.
```

```
r2
        if seismic zone = 2,
                &special structure = no,
        then path1 = ng.
r3
        if seismic zone gt 2
                &soil type#soft soil,
                &liquefaction potential#high,
                &variable soil conditions across the site = no,
                &smallest distance tu an active fault = more thann two
miles,
        then path1 = ok.
r4              if seismic zone = 2
                &special structure = yes,
                &soil type#soft soil,
                &liquefaction potential#high,
                &variable soil conditions across the site = no,
                &smallest distance tu an active fault = more thann two
                miles,
        then path1 = ok.
r5
        if path1 = ok,
                &building status = existing,
                &shape in plan = other,
        then path2 = ng.
r6
        if path1 = ok,
                &building status = new,
        then path2 = ok.
r7
        if path1 = ok,
                &building status = existing,
                &shape in plan = square or rectangular or circular,
        then path2 = ok.
r8
        if path2 = ok,
                &structural system = steel frame,
                &building height range#less thann thirty five feet,
        then path3 = ng.
r9
        if path2 = ok,
                &structural system = reinforced concrete frame,
                &building height range = between sixty seven and
                hundred feet,
                /building height range = more thann hundred feet,
        then path3 = ng.
r10
        if path2 = ok,
                &structural system = shear wall system,
                &building height range = more thann hundred feet,
        then path3 = ng.
```

r11

if path2 = ok,
&structural system = shear wall system,
&building height range = between sixty seven and hundred feet,
&building depth range = less thann fifty feet,
then path3 = ng.

r12

if path2 = ok,
&structural system = shear wall system,
&building height range = between thirty five and sixty seven feet,
/building height range = less thann thirty five feet,
then path3 = ok.

r13

if path2 = ok,
&structural system = shear wall system,
&building height range = between sixty seven and hundred feet,
&building depth range = more thann fifty feet,
then path3 = ok.

r14

if path2 = ok,
&structural system = reinforced concrete frame,
&building height range = between thirty five and sixty seven feet,
/building height range = less thann thirty five feet,
then path3 = ok.

r15

if path2 = ok,
&structural system = steel frame,
&building height range = less thann thirty five feet,
then path3 = ok.

r16

if path3 = ok,
&cost of base isolation solution = more thann thirty dollars per square foot,
then decision = the base isolation solution is not recommended.

r17

if path3 = ok,
&cost of base isolation solution = between fifteen and thirty dollars per square foot,
then decision = more detailed analysis is requested.

r18

if path3 = ok,
&cost of base isolation solution = less thann fifteen dollars per square foot,
then decision = the base isolation solution is recommended

```
%
actions:
obtain path1.
if path1 = ng,
then message "the base isolation solution is not recommended"
endif.
if path1 = ng, then pause
endif.
obtain path2.
if path2 = ng,
then message "the base isolation solution is not recommended"
endif.
if path2 = ng,
then pause
endif.
obtain path3.
if path3 = ng,
then message "the base isolation solution is not recommended"
endif.
if path3 = ng,
then pause
endif.
if shape in plan = other,
then message "please estimate the cost taking into account seismic
joints for "
"the design solution"
endif.
obtain decision.
message "after the screening procedure I consider that".
display value(decision).
pause
%
```

APPENDIX B

SEAOC DESIGN CRITERIA FOR HOSPITALS

DRAFT

# SEISMIC ISOLATION DESIGN GUIDELINES FOR HOSPITALS

## 1. INTRODUCTION

This document provides guidelines for the design of hospital structures which use seismic (base) isolation systems as an alternative structural system permitted by Section 2-2312(a) of Title 24, California Administrative Code (CAC).

Complete project description and design criteria should be provided to the Office of Statewide Health, Planning and Development (OSHPD) for review by the Office of the State Architect (OSA) prior to submission of construction documents for checking.

## 2. DETERMINATION OF DISPLACEMENT AND FORCES

Seismic isolation design forces and displacements should be obtained from dynamic analyses using seismic input corresponding to the maximum probable and maximum credible events.

### 2.1 Analysis Procedures - General

Analytical models of the building should consider the three-dimensional aspects of the structural system and should accurately represent both the deformational characteristics of the isolation system and the deformational characteristics of the superstructure. Analysis of lateral response should be performed in both orthoginal directions of the building. The isolation system and the superstructure may be analyzed as being linear as long as response is nearly-elastic. Suggested criteria for determining nearly-elastic structural behavior are given in Appendix A.

## 2.2 Analysis Procedures - Isolation System

The deformational characteristics of the isolation system should be explicitly modeled and substantiated by test, as specified in Section 6. The deformational characteristics of the isolation system should account for the spatial distribution and variation in isolator stiffness.

It is not necessary for the building model used for analysis of the isolation system to be a member-by-member representation of the superstructure. Provided the essential dynamic characteristics are accurately represented, the building model may utilize a "stick" model representation of the superstructure.

If the deformational characteristics of the isolation system are not stable or vary appreciably with the nature of the load (e.g., rate, amplitude, or time dependent), then design displacements should be based on the deformational characteristics of the isolation system which give the largest possible deflection (e.g., minimum effective stiffness of isolators), and the design forces should be based on the deformational characteristics of the isolation system which give the largest possible force (e.g., maximum effective stiffness of isolators).

If the deformational characteristics of the isolation system are not stable or vary appreciably with the nature of the load (e.g., rate, amplitude, or time dependent), then the hysteretic behavior (i.e., damping) used to determine design displacements and forces should be based on the deformational characteristics of the isolation system which represent the minimum amount of energy dissipated during cyclic response.

### 2.3 Horizontal Torsional Moments

Provisions should be made for the increase in response resulting from horizontal torsion due to an eccentricity between the center of mass and the center of rigidity. Accidental torsion should be accounted for in analysis by placing floor mass a distance from the calculated location equal to ±5% of the building dimension perpendicular to the direction under consideration.

### 2.4 Time History Analysis

Time history is required for buildings which have either a nonlinear isolation system or a nonlinear superstructure. If time history analysis is performed, at least three appropriate time histories, as defined in Section 3, should be used for each level of seismic input. Explicit modeling of deformational characteristics should consider both minimum and maximum effective stiffness of the isolation system. This may require two separate analyses for each time history used. The maximum response of all required analyses should be used for design.

If minimum and maximum effective stiffness of the isolation system do not differ by more than 10%, then only one analysis per time history would be sufficient using deformational characteristics which represent an average value of effective stiffness.

### 2.5 Response Spectrum Analysis

If a response spectrum analysis is used (i.e., for linear systems), two separate analyses should be performed for each level of seismic input, one using maximum effective stiffness and the other using minimum effective stiffness of the isolation system. In both cases, the minimum effective damping value at the design displacement should be used. Guidance for evaluation of minimum and maximum effective stiffness and minimum effective damping are given in Appendix B. The maximum response of all required analyses should be used for design.

If minimum and maximum effective stiffness of the isolation system do not differ by more than 10%, then only one response spectrum analysis is required using an average value of effective stiffness.

## 3. SEISMIC INPUT

The site-specific ground motion should be based on appropriate geologic, tectonic, seismic, and foundation material information. The two levels of ground motion which should be considered are as defined in Section 2-2312(d) 1A of Part 2, Title 24, CAC.

If time history analysis is used, the input time histories should be selected from different recorded events and based on similarity to source magnitude, foundation material and tectonic conditions. They should be scaled such that their 5%-damped response spectrum essentially envelopes the site-specific spectrum and does not fall below the site-specific spectrum by more than 10% at any period. Time histories developed for sites within 10 km of a major active fault must incorporate near-fault phenomena. Duration of time histories should be consistent with the magnitude and source characteristics of an event.

## 4. LATERAL DESIGN FORCE AND DESIGN DISPLACEMENT

### 4.1 Isolation System

Displacements and forces used for design of the isolation system and connections to structural elements immediately above and below the isolation system should be 1.5 times the maximum displacements and forces determined from dynamic analysis using the maximum probable earthquake, or 1.1 times the maximum displacements and forces determined from dynamic analysis using the maximum credible earthquake, whichever is greater.

### 4.2 Structural Elements Below the Isolation Interface

The strength of the elements below the isolation interface should not be less than that required to sustain the lateral forces, as determined by dynamic analysis for the maximum credible earthquake, together with either a factored load of 1.2 times the dead load plus 0.5 times the reduced live load, or 0.8 times the dead load, whichever is greater.

### 4.3 Structural Elements Above the Isolation Interface

#### 4.3.1 Maximum Probable Earthquake

Using the dynamic analysis for the maximum probable earthquake, structural members should be proportioned on the basis of their maximum capacity, otherwise known as yield or limit strength design in accordance with Section 2-2312(d) 1D, or on the basis of the deflection or drift limitations set forth in Section 2-2307, whichever governs.

The base shear forces resulting from this analysis should be compared with:

a. the base shear corresponding to the design wind load and

b. the yield level of a softening system, the ultimate capacity of a sacrificial wind-restraint system, and the static friction level of a sliding system.

If the dynamic analysis base shear force for the superstructure is less than these limits, the design forces should be increased proportionately so that the greater of the limits is satisfied.

#### 4.3.2 Maximum Credible Earthquake

Using the dynamic analysis for the maximum credible earthquake, ductile moment resisting frame structures should be designed so that Section 2-2312(d) 1F is satisfied.

For other types of framing, or for highly irregular or unusual buildings, other criteria as determined by the project architect or structural engineer and approved by the Office of the State Architect will be required to demonstrate safety against collapse from the maximum credible earthquake.

# 5 ADDITIONAL REQUIREMENTS

## 5.1 Isolation System

### 5.1.1 Back-up System

An alternate vertical load-carrying system should be provided in case of isolation system failure.

### 5.1.2 Environmental Conditions

In addition to the requirements for vertical and lateral loads induced by wind and earthquake, the isolation system should be designed with consideration given to other environmental conditions including aging effects, creep, fatigue, operating temperature and exposure to moisture or damaging substances.

### 5.1.3 Wind Loads

Isolated structures should resist design wind loads at all levels above the isolator level in accordance with Title 24 wind design provisions. At the isolator level, a wind restraint system should be provided as necessary to avoid human discomfort within the building and as necessary to limit lateral displacement in the isolation system to a value equal to that required between floors.

### 5.1.4 Fire Resistance

Fire resistance for the isolation system should meet that required for the building's columns, walls, or other structural elements.

### 5.1.5 Lateral Restoring Force

The isolation system should be configured to produce a restoring force sufficient to ensure that the maximum offset of any isolator unit does not exceed 33% of the design displacement. This requirement ensures that the isolation system will not have significant residual displacement following an earthquake, such that the isolated structure will be: 1) stable; and 2) in a condition to survive aftershocks and future earthquakes.

The isolation system need not be configured to produce a restoring force, as required above, provided the isolation system is capable of remaining stable under full vertical load and accommodating lateral displacements equal to four times the maximum offset. Isolation systems which are not configured to produce a lateral restoring should be capable of accommodating displacements significantly greater than the design displacement. Such displacements could occur in these systems as a result of directional biases in vibratory response, earthquakes with multiple segments of strong motion, or as a result of aftershocks.

### 5.1.6 Vertical Load Stability

The isolation system should provide a factor of safety of three (3) for vertical loads (dead load plus live load) in its laterally undeformed state. It should also be designed to be stable under the full design vertical loads at a horizontal displacement which is the greater of either 1.25 times the design displacement or four times the maximum offset for softening systems and sliding systems, or 1.25 times the design force for hardening systems.

The factor of safety of three for vertical loads was obtained from the NBS Special Publication 577 entitled "Development of a Probability Based Load Criterion for American National Standard A58."

The application of the factor of safety of three will be dependent on the type of isolation system, but should be applied as a well-defined limiting stress or strain value. For example, systems with roller bearings may be governed by contact pressure, and systems with elastomeric bearings, may be governed by the tensile strain in the rubber.

An additional consideration for systems that incorporate an element that can overturn (e.g., elastomeric bearing with a dowel shear transfer mechanism) is the stability of the element at a horizontal displacement which is the greater of either 1.25 times the design displacement or four times the maximum offset. The required check of stability will ensure that there is sufficient margin prior to any loss of vertical load support capacity.

### 5.1.7 Overturning

The factor of safety against global structural overturning at the isolation level should not be less than 1.0 for the maximum credible event. Local uplift of individual elements is permitted provided the resulting deflections do not cause overstress or instability of building elements.

The intent of this requirement is to prevent global structural overturning and overstress of elements due to local uplift for the maximum credible event. Uplift in a braced frame or shear wall is acceptable provided the isolation system does not disengage from its horizontal resisting connection detail. The connection details used in some isolation systems are such that tension is not permitted on the system. If the tension capacity of an isolation system is to be utilized on resisting uplift forces, then component tests should be performed to demonstrate the adequacy of the system on resisting tension forces at the design displacement.

If an isolation system is designed to resist tensile forces, then this vertical load case should be included in the sequence of tests specified in Section 6.2(2).

### 5.1.8 Inspection and Replacement

Access for inspection and replacement of the isolation system should be provided.

The isolation system may sustain damage and the building may develop offsets as a result of extreme ground motion. After an earthquake, the building should be inspected for offset and possible damage to the isolation system. Damaged elements should be replaced or repaired. If offset in the isolation system is appreciable, then consideration should be given to jacking the building back to its original position, replacing damaged isolators, or altering the isolation system.

### 5.1.9 Quality Control

A quality control testing program for the isolation system should be established by the design structural engineer.

For systems based in whole or in part on an elastomeric bearing, this should include:

a) All bearings should be tested in compression for 1.5 (DL + LL) in accordance with ASTM D-4014-81.

b) Twenty percent (20%) of all bearings should be tested in combined compression and shear with the actual dead load to 50% shear strain in the elastomer.

c) Destructive testing to determine fatigue and bond strengths should be performed on samples of at least one bearing on each project. Tests should comply with Part I of Caltrans Test Method 663-1978.

A test and inspection program is necessary for both fabrication and installation of the isolation system. Because seismic isolation is a developing technology, it may be difficult to reference standards for testing and inspection. Reference can be made to standards for some materials such as elastomeric bearings (ASTM D4014-81 and British standards). Similar standards are required for other isolation systems. Special inspection procedures and load testing to verify manufacturing quality should be developed for each project. The requirements will vary with the type of isolation system used.

## 5.2 Structural System

### 5.2.1 Lateral Drift

The structure above the isolation system should conform to drift criteria of Title 24 for the maximum probable earthquake.

### 5.2.2 Horizontal Distribution of Force

A horizontal diaphragm or other structural elements located immediately above the isolation system should provide continuity between individual isolators, should have adequate rigidity to ensure that the building structure moves as a rigid body on top of the isolators, and should be strong enough to transmit forces (due to non-uniform ground motion) from one part of the building to another.

### 5.2.3 Separations

Minimum separations between the isolated building and surrounding retaining walls or other fixed obstructions should be not less than 1.1 times the design displacement, four times the maximum offset, or the minimum distance required for conventional structures.

## 5.3 Nonstructural Components

### 5.3.1 Components Above the Isolation Interface

Design of nonstructural component anchorage or bracing should be consistent with the response of the particular structure under consideration, as substantiated by analysis and/or tests for the maximum credible event. Alternatively, anchorage or bracing may be designed using the force requirements of Tile 24 for non-base isolated structures.

### 5.3.2 Components Which Cross the Isolation Interface

All architectural, equipment and utility components which cross the seismic interface should be designed to accommodate 1.1 times the design displacement.

To accommodate the differential movement between the isolated building and the ground, provisions for flexible utility connections should be made. In addition, rigid structures crossing the interface, such as stairs, elevator shafts, and walls, should have details to accommodate differential motion at the isolator level without sustaining damage sufficient to threaten life safety.

## 6. REQUIRED TESTS OF THE ISOLATION SYSTEM

### 6.1 General

The deformation characteristics and damping values used in the design and analysis should be based on existing test data of the system and confirmed by the following tests on a selected sample of the components prior to construction. The isolation system tested should include the ultimate restraint system and the wind restraint system if such systems are used in the design. They should not be considered as manufacturing quality control requirements.

The design displacement and forces developed from these provisions are predicated on the basis that the deformational characteristics of the base isolation system have been previously defined by a comprehensive set of tests. If a comprehensive amount of test data are not available on a system, then major design alterations in the building may be necessary after the tests are complete. This would result from variations in the isolation system properties assumed for design and those obtained by test. Therefore, it is advisable that prototype systems be tested during the early phases of design if insufficient test data are not available on an isolation system.

## 6.2 Sequence of Tests

The following sequence of tests should be performed on at least two components of the full-size isolation system. The test specimens should include the ultimate restraint system, the wind restraint system, as well as the individual isolators, if such systems are used in the design. Specimens tested should not be used for construction.

Each set of tests should be performed at three different rates of loading. The rate of loading should correspond to 1/2, 1, and 2 times the inverse of the isolated period, defined as a cycle of maximum response for the maximum credible event.

1. Twenty fully reversed cycles of loading at a force corresponding to the design wind force. If a sacrificial wind restraint system is to be utilized, its ultimate capacity should be established by test.

2. Three fully reversed cycles of loading at each of the following increments of the design displacement or design force of Section 4: 0.25, 0.50, 0.75, 1.0, and 1.25.

   a. For softening systems, a displacement-controlled test should be performed with the specified increments based on the design displacement of Section 4.1.

   b. For hardening systems, a force-controlled test should be performed with the specified increments based on the maximum force of Section 4.1.

   Exception: If variations in effective stiffness greater than $\pm$ 15% occur in these three cycles of loading at a given amplitude, then three additional cycles of loading at the given amplitude should be performed.

3. Ten fully reversed cycles of loading at 1.0 times the design displacement.

If an isolator is also a vertical load carrying element the above sequence of tests should be performed for each of three different vertical loads as follows:

i) DL
ii) DL + 20% DL + 50% Overturning Force
iii) DL - 20% DL - 50% Overturning Force

For each cyclic test the force deflection and hysteretic behavior of the test specimen should be recorded. The vertical load carrying elements of the isolation system should also be statically load tested to demonstrate stability under a vertical load of 1.5 times dead load plus reduced live load plus seismic overturning at 1.0 times the design displacement.

The required sequence of tests will experimentally verify:

1. The assumed stiffness and capacity of the wind restraining mechanism.

2. The variation in the isolator's deformational characteristics with rate of loading, amplitude, and with vertical load, if it is a vertical load-carrying member.

3. The variation in the isolator's deformational characteristics for a realistic number of cycles of loading at the design displacement.

Force-deflection tests are not required if similar-sized components have been previously tested using the specified sequence of tests.

Variations in effective stiffness greater then + 15% would require an additional 3 cycles of loading at a given amplitude to determine if deterioration continues and variations greater than ± 20% would be cause for concern. The variations in the vertical loads required for tests of isolators which carry vertical, as well as lateral loads, are necessary to determine possible variation in the system properties due to vertical ground acceleration and overturning force. Test set-ups may not be capable of incorporating very low vertical loads because of static instability in the test assembly. Consequently, a compromise may be required to set a limit on the lower vertical load. Clearly, the engineer will have to use judgement in selecting the appropriate dead loads and overturning forces for the test system because these will vary throughout the structure. As noted in Section 6.3, the design values of the isolation system are based on the full DL tests provided the average results of the other two vertical load tests do not vary by more than 10% from the DL tests. This requirement is based on the premise that the overturning forces are equal and opposite.

## 6.3 System Adequacy

The seismic isolation system test performance may be assessed as adequate if:

1. The test force-deflection plots for all tests specified in Section 6.2 have a positive incremental stiffness.

2. There is less than a 20% deterioration in the equivalent stiffness for the six cycles of test (if six are performed at a given vertical load specified in Section 6.2 (2)).

3. There is a less than 25% deterioration in the equivalent stiffness and damping values for the 10 cycles of tests at a given vertical load specified in Section 6.2(3).

An incremental reduction in load resistance over a displacement range greater than 1/2 inch is indicative of deterioration or instability, neither of which can be tolerated for the specified tests. If this occurs, then the tests should be extended so that at least another 3 cycles of loading are required with a 25% increase in the test amplitude or force at which this phenomena was observed. If reduction in load resistance continues, then the system is inadequate.

If the variation in stiffness and damping values for a given vertical load are less than 25%, then the system is adequate. If the variations are greater than 40%, then the seismic isolation system should not be used. Variations between 25% and 40% would be cause for concern and should probably require tests on additional isolators.

## 7. MONITORING AND INSTRUMENTATION

The isolation system should be monitored for the life of the building, and access for inspection and replacement of the system should be provided. A program for monitoring should be established by the person responsible for the structural design and would be submitted for approval with the plans and specifications. The monitoring program would become a part of the approval. The implementation and maintenance of the program should then be the responsibility of the owner of the building. Approval and enforcement of this program would be delegated to the Office of the State Architect by the Office of State Health Planning and Development.

As a minimum, the program should include the following:

1. Approved instrumentation would be provided and maintained to record structural motion at appropriate locations within the building and at the levels of the bottom and the top of the isolators. Verified reports confirming adequate maintenance and monitoring of the instruments should be submitted to the Office of the State Architect semi-annually. Hard copies of accelerograms should be submitted to OSA within one month of a recorded event. Records for significant events as described in 2. should be accompanied by appropriate response spectra.

2. Visual inspections should be made by a Structural Engineer after every significant earthquake (defined as an earthquake

large enough to produce a ground motion peak acceleration of 0.2g or larger or a displacement record of two inches or greater at the base of the isolators). The inspection should consist of viewing the structural performance of the building, the records produced by the building instrumentation, and a visual examination of the isolators and their connections for deterioration, offset, or physical damage. A report of such inspection, including an analysis for the recorded ground motion and conclusions on the continuing adequacy of the structure, should be submitted to OSA for review within three months of such an event.

3. Selected isolators (approximately two percent of the total, but not less than two) should be removed temporarily at intervals not to exceed 10 years for physical testing. Tests should determine lateral stiffness under the design dead load and design displacement. The results of these test should be compared to the data obtained by the qualification testing. If the mean value of the material properties determined by the testing vary by more than one standard deviation of the qualification test data from that data, the analysis of the structure-base isolation model should be repeated to verify that the design is still valid. A report of the results of testing, including conclusions on the continuing adequacy of the structure and isolators, should be submitted to OSA for review within three months of the testing.

## APPENDIX A

### Suggested Criteria for Determining Nearly Elastic Structural Behavior

The following concepts have been extracted from "Seismic Design Guidelines for Essential Buildings", Department of the Army, TM5-809-10-1. If additional clarification or examples are required, then reference to that document is recommended. These concepts are incorporated solely for the purpose of defining when linear model of the superstructure is appropriate for dynamic analysis.

Nearly elastic behavior is interpreted as allowing some structural elements to exceed their strength level within specific limits. If the structural response is within the limits required for nearly elastic behavior, then the structural deformations may be assumed to be equal to those found by the use of a linear model of the structure. For a structure that has a multiplicity of structural elements that form the lateral-force-resisting system, the yielding of a small number of elements will generally not affect the overall elastic behavior of the structure if the excess load can be distributed to other structural elements that have not exceeded their yield strength.

A linear model of the superstructure is acceptable if the procedure that evaluates overstresses of individual elements, outlined below, is followed, and the limits given in Table A-1 are not exceeded.

1. Perform analysis of the structure using the appropriate maximum credible earthquake response spectrum or time histories.

2. Calculate the forces on all of the structural elements. Load combinations are given below and are in Section 2-2312(d) 1D. These forces will be defined as the demand forces and denoted with subscript D (e.g., $M_D$, $V_D$, $F_D$).

   Demand Force = 1.2D + 0.5L + E

   Demand Force = 0.8D + E

where:

L = reduced live load

E = earthquake force from (1)

3. Calculate the elastic capacities of all the structural elements in the same force units used in paragraph (2) above. These forces will be defined as the capacity forces and denoted with the subscript C (e.g., $M_C$, $V_C$, $F_C$).

The elastic capacity is set to equal the strength capacities of the structural components.

a. Reinforced Concrete: The strength capacity for reinforced concrete elements will be given by the ACI Building Code 318.

b. Structural Steel: In lieu of strength design criteria for structural steel, the working stresses for ordinary or nonseismic construction may be increased by 70 percent to provide the strength capacity; for example,

$$\frac{f_a}{F_a} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.7$$

c. Reinforced Masonry Design: In lieu of a strength design criteria for reinforced masonry, working stresses for ordinary or nonseismic construction may be increased by 70 percent to provide the strength capacity; for example, $f_a \leq 1.7\ F_a$.

d. Connections: All connections that do not develop the strength of the connecting members will have a strength reduction factor of 0.75. This reduction factor will be applied to the strength capacity of the connection material.

4. Calculate the ratio of the demand forces to the capacity forces of all the structural elements. These ratios will be defined as inelastic demand ratios.

5. Review the inelastic demand forces for uniformity, symmetry, mechanisms, and relative values. Compare values to limits set forth in Table A-1. If any of the following conditions exist, a linear model representation of the structure is not acceptable and the structure must be analyzed by developing a simplified inelastic representation of the building which incorporates the progressive inelastic deformation of the structural members.

   a. Exceeding the inelastic demand ratios of Table A1.
   b. Unsymmetrical yielding, on a horizontal plane in the structure, that will decrease the torsional resistance.
   c. Hinging of columns at a single story level that will cause a mechanism.
   d. Discontinuity in vertical elements that can cause instability or fracture.
   e. Unusual distributions of inelastic demand ratios.

6. Engineering judgment is required for the structural evaluation of the post-yield analysis. If the review of the inelastic demand ratios satisfies the requirements of paragraph (5) above, it may be assumed that the inelastic deformations can be adequately approximated by elastic analysis.

**A-1 - Limits on Inelastic Demand Ratios**

| Building System | Element | Demand Ratios |
|---|---|---|
| Steel DMRSF | Beams | 2.0 |
| | Columns | 1.25 |
| Braced Frames | Beams | 1.5 |
| | Columns | 1.25 |
| | Diag. Braces | 1.25 |
| | K-Braces | 1.0 |
| | Connections | 1.0 |
| Concrete DMRSF | Beams | 2.0 |
| | Columns | 1.25 |
| Concrete Walls | Shear | 1.25 |
| | Flexure | 2.0 |
| Masonry Walls | Shear | 1.1 |
| | Flexure | 1.5 |

## APPENDIX B

### Determination of Effective Stiffness and Damping

The intent of these requirements is to ensure that the deformational properties used in design result in the maximum design forces and displacements. For determining design displacement, this means using the lowest damping value and minimum effective stiffness of the isolation system. For determining design forces, this means using the lowest damping value and maximum effective stiffness of the isolation system.

### B.1 Stiffness and Damping Properties

The effective stiffness, and equivalent viscous damping to be used to determine the design base shear forces and displacements by response spectrum analysis may be determined as follows:

1. The minimum stiffness, $k_{min}$, to be used in the determination of the design displacement should be based on the average of the lowest three effective stiffness values determined from each of the 10 cycles of loading in the test sequence specified in 6.2(3) for the dead load test, provided these lowest three values do not differ by more than 15%. If they do, then the lowest value should be used.

2. The maximum stiffness, $k_{max}$, to be used in the determination of the design base shear force should be based on the average of the highest three effective stiffness values determined from each of the 10 cycles of loading in the test sequence specified in 6.2(3) for the dead load test provided these highest three values do not differ by more than 15%. If they do, then the highest value should be used.

3. The equivalent viscous damping, if it is to be used in a linear system in the determination of the design displacement, should be based on the average of the lowest three equivalent viscous

damping values determined from each of the 10 cycles of loading In the test sequence specified in 6.2(3) for the dead load test, provided the lowest three values do not differ by more than 15%. If they do, then the lowest value should be used.

4. For isolation systems that act as vertical load-carrying members, the test sequence specified in 6.2(3) is required for 3 different vertical loads. Items (1), (2), and (3) above, are based on the vertical dead load test results provided the average equivalent stiffness and damping values for each of the 10 test cycles for all greater and lesser vertical load tests are within 15% of the corresponding average values of the dead load vertical test. If they are not, then Items (1), (2), and (3) above should be based on the appropriate highest or lowest values from the three sets of vertical load tests.

B.2 Determination of Stiffness Characteristics

The effective stiffness of the system at each test displacement should be calculated for each cycle of loading as follows:

$$k_{eff} = \frac{F_p - F_n}{\Delta_p - \Delta_n}$$

where, $F_p$, $\Delta_p$, and $F_n$, $\Delta_n$ are the maximum positive and negative forces and displacements, respectively. If the minimum effective stiffness is to be determined then $F_{p,min}$, and $F_{n,min}$ should be used in the equation. If the maximum effective stiffness is to be determined, then $F_{p,max}$ and $F_{n,max}$ should be used in the equation.

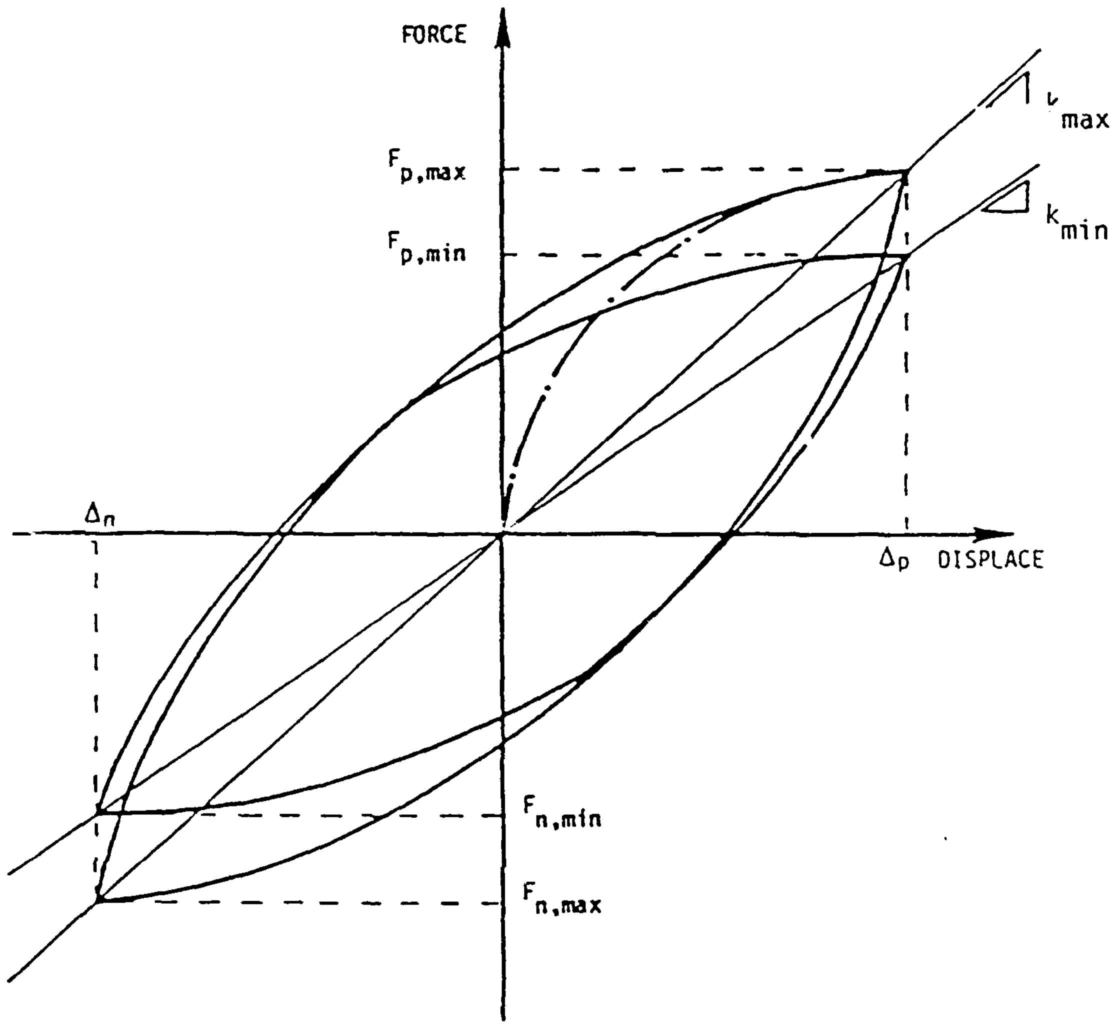
The effective stiffness is determined from the hysteresis loops shown in Figure B1. Stiffness may vary considerably as the test amplitude increases, but should be reasonably stable ($\pm$ 10%) for more than one cycle at a given amplitude.

## B.3 Determination of Damping Characteristics

The equivalent viscous damping ratio ( $\beta$ ) for systems with velocity-related damping for each cycle of loading shall be calculated as:

$$\beta = \frac{1}{2\pi} \quad \frac{\text{Area of Hysteresis Loop}}{k_{eff}\,\Delta^2{}_{max}}$$

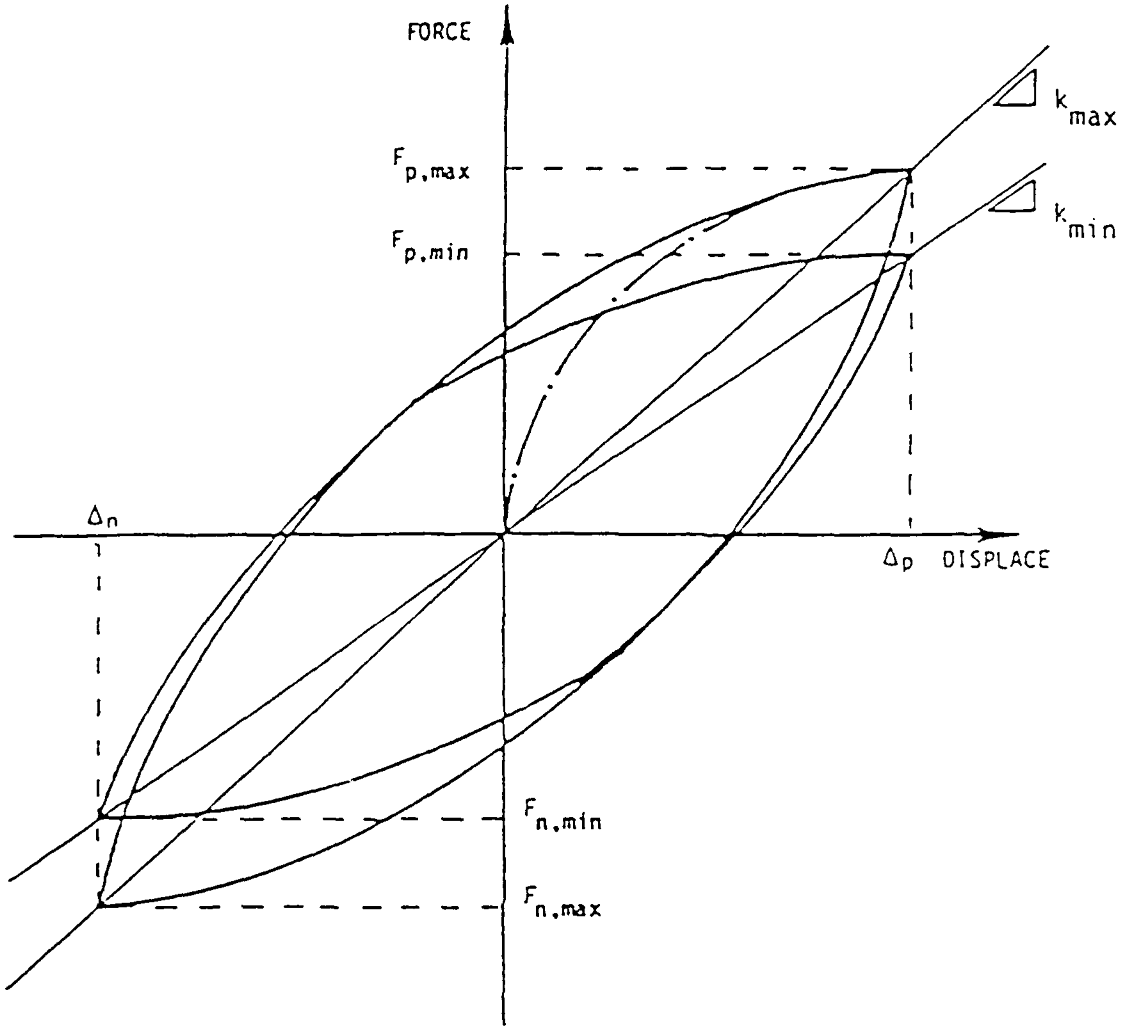
The determination of equivalent viscous damping is reasonably reliable for systems whose damping characteristics are velocity-dependent. For systems that have amplitude-dependent energy-dissipating mechanisms, significant problems arise in determining an equivalent viscous damping value, since it is difficult to relate velocity and amplitude-dependent phenomena. The equivalent viscous damping concept can only be used for linear systems since nonlinear systems must be modeled explicitly.




$$k_{max} = \frac{F_{p,max} - F_{n,max}}{\Delta_p - \Delta_n}$$

$$k_{min} = \frac{F_{p,min} - F_{n,min}}{\Delta_p - \Delta_n}$$

FIGURE B-1: EXAMPLE FORCE-DEFLECTION TEST CURVES USED TO DETERMINE MAXIMUM AND MINIMUM EFFECTIVE STIFFNESS




$$k_{max} = \frac{F_{p,max} - F_{n,max}}{\Delta_p - \Delta_n}$$

$$k_{min} = \frac{F_{p,min} - F_{n,min}}{\Delta_p \quad \Delta_n}$$

FIGURE B-1: EXAMPLE FORCE-DEFLECTION TEST CURVES USED TO DETERMINE MAXIMUM AND MINIMUM EFFECTIVE STIFFNESS

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ARMY ENGR DIV CEEUD-ED-TA (McVay), Frankfurt, GE; CEHND-ED-CS, Huntsville, AL; ED-SY (Loyd), Huntsville, AL; HNDED-SY, Huntsville, AL
ARMY EWES GP-EC (Webster), Vicsburg, MS; Library, Vicksburg MS; WESCD-P (Melby), Vicksburg, MS; WESCV-Z (Whalin), Vicksburg, MS; WESGP-E, Vicksburg, MS
ARMY LMC Fort Lee, VA
ARMY MISSILE R&D CMD Ch, Docs, Sci Info Ctr, Arsenal, AL
ARMY MMRC DRXMR-SM (Lenoe), Watertown, MA
ADMINSUPU PWO, Bahrain
BUREAU OF RECLAMATION D-1512 (GS DePuy), Denver, CO
CBC Code 10, Davisville, RI; Code 15, Port Hueneme, CA; Code 155, Port Hueneme, CA; Code 430, Gulfport, MS; Library, Davisville, RI; PWO (Code 400), Gulfport, MS; PWO (Code 80), Port Hueneme, CA; Tech Library, Gulfport, MS
CNA Tech Library, Alexandria, VA
COGARD R&DC Library, Groton, CT
COMCBLANT Code S3T, Norfolk, VA
COMDT COGARD Library, Washington, DC
COMFLEACT PWO, Sasebo, Japan
COMNAVSUPPFORANTARCTICA DET, PWO, Christchurch, NZ
COMNAVSURF Code N42A, Norfolk, VA
COMOCEANSYS Lant, Code N9, Norfolk, VA
COMTRA Lant, SCE, Norfolk, VA
DFSC OWE, Alexandria, VA
DIA DB-6E1, Washington, DC; DB-6E2, Washington, DC; VP-TPO, Washington, DC
DIRSSP Tech Lib, Washington, DC
DOD DFSC-FE, Cameron Station, Alexandria, VA; Explos Safety Brd (Lib), Washington, DC
DOE Wind/Ocean Tech Div, Tobacco, MD
DTIC Alexandria, VA
DTRCEN Code 172, Bethesda, MD; Code 4111, Bethesda, MD
FAA Code APM-740 (Tomita), Washington, DC
GIDEP OIC, Corona, CA
GSA Ch Engrg Br, PQB, Washington, DC
LIBRARY OF CONGRESS Sci & Tech Div, Washington, DC
MARCORBASE Code 4.01, Camp Pendleton, CA; Code 406, Camp Lejeune, NC; PAC, PWO, Camp Butler, JA; PWO, Camp Lejeune, NC; PWO, Camp Pendleton, CA; Pac, FE, Camp Butler, JA
MARCORPS FIRST FSSG, Engr Supp Offr, Camp Pendleton, CA
MCAS PWO, Yuma, AZ
MCLB PWC (Sachan), Barstow, CA
MCRD PWO, San Diego, CA
MCRDAC M & L Div Quantico, VA; PWO, Quantico, VA
NAF AROICC, Midway Island; Dir, Engrg Div, PWD, Atsugi, Japan

NAS Chase Fld, Code 18300, Beeville, TX; Chase Fld, PWO, Beeville, TX; Code 110, Adak, AK; Code 15, Alameda, CA; Code 1833, Corpus Christi, TX; Code 70, South Weymouth, MA; Code 8, Patuxent River, MD; Code 83, Patuxent River, MD; Miramar, PWO, San Diego, CA; NI, Code 183, San Diego, CA; Fac Mgmt Offc, Alameda, CA; PW Engrg (Branson), Patuxent River, MD; PWO (Code 182) Bermuda; PWO, Adak, AK; PWO, Cecil Field, FL; PWO, Dallas, TX; PWO, Glenview, IL; PWO, Keflavik, Iceland; PWO, Key West, FL; PWO, Kingsville TX; PWO, New Orleans, LA; PWO, Sigonella, Italy; PWO, South Weymouth, MA; SCE, Barbers Point, HI; SCE, Cubi Point, RP; Whiting Fld, PWO, Milton, FL

NAVAIRDEVCEN Code 832, Warminster, PA

NAVAIRENGCEN Code 182, Lakehurst, NJ; PWO, Lakehurst, NJ

NAVAIRTESTCEN PWO, Patuxent River, MD

NAVAUDSVCHQ Director, Falls Church VA

NAVAVNDEPOT Code 640, Pensacola, FL

NAVCHAPGRU Code 60, Williamsburg, VA

NAVCOASTSYSCEN CO, Panama City, FL; Code 2360, Panama City, FL; Code 740, Panama City, FL; Tech Library, Panama City, FL

NAVCOMMSTA Code 401, Nea Makri, Greece

NAVELEXCEN DET, OIC, Winter Harbor, ME

NAVEODTECHCEN Tech Library, Indian Head, MD

NAVFAC PWO (Code 50), Brawdy Wales, UK; PWO, Oak Harbor, WA

NAVFACENGCOM Code 00, Alexandria, VA; Code 03, Alexandria, VA; Code 03T (Essoglou), Alexandria, VA; Code 04A, Alexandria, VA; Code 04A1, Alexandria, VA; Code 04A1D, Alexandria, VA; Code 04A3, Alexandria, VA; Code 04A3C, Alexandria, VA; Code 0631, Alexandria, VA; Code 07, Alexandria, VA; Code 07M (Gross), Alexandria, VA; Code 09M124 (Lib), Alexandria, VA

NAVFACENGCOM - CHES DIV, FPO-1PL, Washington, DC

NAVFACENGCOM - LANT DIV, Br Ofc, Dir, Naples, Italy; Code 1112, Norfolk, VA; Library, Norfolk, VA

NAVFACENGCOM - NORTH DIV, Code 04, Philadelphia, PA; Code 04AL, Philadelphia, PA

NAVFACENGCOM - PAC DIV, Code 09P, Pearl Harbor, HI; Library, Pearl Harbor, HI

NAVFACENGCOM - SOUTH DIV, Code 04A3, Charleston, SC; Code 1112, Charleston, SC; Code 406, Charleston, SC; Library, Charleston, SC

NAVFACENGCOM - WEST DIV, Code 04A2.2 (Lib), San Bruno, CA; Code 04B, San Bruno, CA; Code 408.2 (Jeung) San Bruno, CA; Pac NW Br Offc, Code C 50, Silverdale, WA

NAVFACENGCOM CONTRACTS AROICC, Quantico, VA; Code 460, Portsmouth, VA; Code 923, Everett, WA; DROICC, Lemoore, CA; Earle, ROICC, Colts Neck, NJ; North Bay, Code 1042.AA, Vallejo, CA; OICC, Guam; OICC ROICC, Norfolk, VA; OICC/ROICC, Virginia Beach, VA; ROICC, Corpus Christi, TX; ROICC, Crane, IN; ROICC, Keflavik, Iceland; ROICC, Point Mugu, CA; SW Pac, OICC, Manila, RP

NAVFUEL DET OIC, Yokohama, Japan

NAVHOSP CO, Millington, TN; Hd, Fac Mgmt, Camp Pendleton, CA; SCE (Knapowski), Great Lakes, IL; SCE, Pensacola, FL

NAVMAG SCE, Subic Bay, RP

NAVMARCORESCEN LTJG Davis, Raleigh, NC

NAVMEDCOM NWREG, Fac Engr, PWD, Oakland, CA; PACREG, Code 22, Barbers Point, HI; SE REG, Hd, Fac Mgmt Dept, Jacksonville, FL; SWREG, Head, Fac Mgmt Dept, San Diego, CA; SWREG, SCE, San Diego, CA

NAVOCEANCOMCEN CO, Guam, Mariana Islands

NAVOCEANO Code 6200 (M Paige), Bay St. Louis, MS

NAVOCEANSYSCEN Code 9642B, San Diego, CA

NAVPGSCOL PWO, Monterey, CA

NAVPHIBASE PWO, Norfolk, VA; SCE, San Diego, CA

NAVSCOLCECOFF Code C35, Port Hueneme, CA

NAVSCSCOL PWO, Athens, GA

NAVSEACENPAC Code 32, San Diego, CA

NAVSEASYSCOM Code PMS296L22 (J Rekas), Washington, DC

NAVSHIPREPFAC Library, Guam; SCE, Subic Bay, RP; SCE, Yokosuka, Japan

NAVSHIPYD Code 202.4, Long Beach, CA; Code 202.5 (Library), Bremerton, WA; Code 440, Portsmouth, NH; Code 443, Bremerton, WA; Library, Portsmouth, NH; Mare Island, Code 202.13, Vallejo, CA; Mare Island, Code 280, Vallejo, CA; Mare Island, PWO, Vallejo, CA; Norfolk, Code 440, Portsmouth, VA; PWO, Bremerton, WA

NAVSTA CO, Long Beach, CA; CO, Roosevelt Roads, PR; Code N4214, Mayport, FL; Engr Div, PWD, Rodman, Panama Canal; Engrg Dir, PWD, Rota, Spain; SCE, San Diego, CA; WC 93, Guantanamo Bay, Cuba

NAVSUPPACT PWO, Naples, Italy

NAVSUPPFAC Contract Admin Tech Library, Diego Garcia

NAVSUPSYSCOM Code 0622, Washington, DC

NAVSWC Code E211 (Miller), Dahlgren, VA; DET, White Oak Lab, Code WSO, Silver Spring, MD

NAVWARCOL Code 24, Newport, RI
NAVWPNCEN AROICC, China Lake, CA; PWO (Code 266), China Lake, CA
NAVWPNSTA Code 092B (Hunt), Yorktown, VA; Dir, Maint Control, PWD, Concord, CA; PWO, Charleston, SC; PWO, Seal Beach, CA; PWO, Yorktown, VA
NAVWPNSUPPCEN PWO, Crane, IN
NETC Code 42, Newport, RI; PWO, Newport, RI
NCR 20, CO
NEESA Code 111E (McClaine), Port Hueneme, CA
NMCB 3, Ops Offr; 40, CO; 5, Ops Dept
NOAA Joseph Vadus, Rockville, MD
NRL Code 2511, Washington, DC; Code 4670 (B. Faraday), Washington, DC
NSC Code 54.1, Norfolk, VA
NSD SCE, Subic Bay, RP
NUSC DET Code 2143 (Varley), New London, CT; Code 44 (RS Munn), New London, CT; Code TA131, New London, CT; Lib (Code 4533), Newport, RI
PACMISRANFAC HI Area, PWO, Kekaha, HI
PHIBCB 1, CO, San Diego, CA; 1, P&E, San Diego, CA; 2, CO, Norfolk, VA
PMTC Code 1018, Point Mugu, CA; Code 5041, Point Mugu, CA
PWC ACE Office, Norfolk, VA; Code 10, Great Lakes, IL; Code 10, Oakland, CA; Code 101 (Library), Oakland, CA; Code 1011, Pearl Harbor, HI; Code 102, Oakland, CA; Code 123-C, San Diego, CA; Code 30, Norfolk, VA; Code 400, Great Lakes, IL; Code 400, Oakland, CA; Code 400, Pearl Harbor, HI; Code 400, San Diego, CA; Code 420, Great Lakes, IL; Code 420, Oakland, CA; Code 420B (Waid), Subic Bay, RP; Code 421 (Kaya), Pearl Harbor, HI; Code 421 (Quin), San Diego, CA; Code 421 (Reynolds), San Diego, CA; Code 422, San Diego, CA; Code 423, San Diego, CA; Code 424, Norfolk, VA; Code 430 (Kyi), Pearl Harbor, HI; Code 500, Great Lakes, IL; Code 500, Oakland, CA; Library (Code 134), Pearl Harbor, HI; Library, Guam, Mariana Islands; Library, Norfolk, VA; Library, Pensacola, FL; Library, Yokosuka, Japan; Tech Library, Subic Bay, RP
SPCC PWO (Code 08X), Mechanicsburg, PA
SUBASE Bangor, PWO (Code 8323), Bremerton, WA
SUPSHIP Tech Library, Newport News, VA
US DEPT OF INTERIOR Natl Park Svc, RMR/PC, Denver, CO
USDA Ext Serv (T Maher), Washington, DC; For Svc Reg 8, (Bowers), Atlanta, GA; For Svc, Reg Bridge Engr, Aloha, OR; For Svc, Tech Engrs, Washington, DC
USNA Ch, Mech Engrg Dept, Annapolis, MD; Ocean Engrg Dept (McCormick), Annapolis, MD; PWO, Annapolis, MD
CALIFORNIA STATE UNIVERSITY C.V. Chelapati, Long Beach, CA
CATHOLIC UNIV of Am, CE Dept (Kim), Washington, DC
CITY OF BERKELEY PW, Engr Div (Harrison), Berkeley, CA
CITY OF LIVERMORE Dackins, PE, Livermore, CA
CLARKSON COLL OF TECH CE Dept (Batson), Potsdam, NY
COLORADO STATE UNIVERSITY CE Dept (Criswell), Ft Collins, CO
CORNELL UNIVERSITY Civil & Environ Engrg (Dr. Kulhawy), Ithaca, NY; Library, Ithaca, NY
DAMES & MOORE Library, Los Angeles, CA
FLORIDA ATLANTIC UNIVERSITY Ocean Engrg Dept (Su), Boca Raton, FL
FLORIDA INST OF TECH CE Dept (Kalajian), Melbourne, FL
GEORGIA INSTITUTE OF TECHNOLOGY CE Scol (Kahn), Atlanta, GA; CE Scol (Swanger), Atlanta, GA; CE Scol (Zuruck), Atlanta, GA
INSTITUTE OF MARINE SCIENCES Library, Port Aransas, TX
JOHNS HOPKINS UNIV CE Dept (Jones), Baltimore, MD
LAWRENCE LIVERMORE NATL LAB FJ Tokarz, Livermore, CA; Plant Engrg Lib (L-654), Livermore, CA
LEHIGH UNIVERSITY Linderman Library, Bethlehem, PA
LONG BEACH PORT Engrg Dir (Allen), Long Beach, CA
MICHIGAN TECH UNIVERSITY CE Dept (Haas), Houghton, MI
MIT Engrg Lib, Cambridge, MA; Lib, Tech Reports, Cambridge, MA; RV Whitman, Cambridge, MA
NATL ACADEMY OF SCIENCES NRC, Naval Studies Bd, Washington, DC
NEW MEXICO SOLAR ENERGY INST Dr. Zwibel, Las Cruces, NM
NEW YORK-NEW JERSEY PORT AUTH Engrg Dept (Yontar), New York, NY
OREGON STATE UNIVERSITY CE Dept (Hicks), Corvallis, OR
PENNSYLVANIA STATE UNIVERSITY Gotolski, University Park, PA; Rsch Lab (Snyder), State College, PA
PORTLAND STATE UNIVERSITY Engrg Dept (Migliori), Portland, OR
PURDUE UNIVERSITY CE Scol (Leonards), W. Lafayette, IN; Engrg Lib, W. Lafayette, IN
SAN DIEGO PORT Port Fac, Proj Engr, San Diego, CA
SAN DIEGO STATE UNIV CE Dept (Krishnamoorthy), San Diego, CA

SEATTLE PORT W Ritchie, Seattle, WA
SEATTLE UNIVERSITY CE Dept (Schwaegler), Seattle, WA
SOUTHWEST RSCH INST Energetic Sys Dept (Esparza), San Antonio, TX; King, San Antonio, TX; M. Polcyn, San Antonio, TX; Marchand, San Antonio, TX
STATE UNIVERSITY OF NEW YORK CE Dept (Reinhorn), Buffalo, NY; CE Dept, Buffalo, NY
TEXAS A&M UNIVERSITY CE Dept (Machemehl), College Station, TX; CE Dept (Niedzwecki), College Station, TX; Ocean Engr Proj, College Station, TX
UNIVERSITY OF CALIFORNIA CE Dept (Fenves), Berkeley, CA; CE Dept (Gerwick), Berkeley, CA; CE Dept (Taylor), Davis, CA; CE Dept (Williamson), Berkeley, CA; Naval Arch Dept, Berkeley, CA
UNIVERSITY OF HARTFORD CE Dept (Keshawarz), West Hartford, CT
UNIVERSITY OF HAWAII CE Dept (Chiu), Honolulu, HI; Manoa, Library, Honolulu, HI; Ocean Engrg Dept (Ertekin), Honolulu, HI
UNIVERSITY OF ILLINOIS Library, Urbana, IL; M.T. Davisson, Urbana, IL; Metz Ref Rm, Urbana, IL
UNIVERSITY OF MICHIGAN CE Dept (Richart), Ann Arbor, MI
UNIVERSITY OF NEBRASKA Polar Ice Coring Office, Lincoln, NE
UNIVERSITY OF NEW MEXICO HL Schreyer, Albuquerque, NM; NMERI (Bean), Albuquerque, NM; NMERI (Falk), Albuquerque, NM; NMERI (Leigh), Albuquerque, NM
UNIVERSITY OF PENNSYLVANIA Dept of Arch (P. McCleary), Philadelphia, PA
UNIVERSITY OF TEXAS CE Dept (Thompson), Austin, TX; Construction Industry Inst, Austin, TX; ECJ 4.8 (Breen), Austin, TX
UNIVERSITY OF WASHINGTON CE Dept (Mattock), Seattle, WA
UNIVERSITY OF WISCONSIN Great Lakes Studies Cen, Milwaukee, WI
WASHINGTON DHHS, OFE/PHS (Ishihara), Seattle, WA
ADVANCED TECHNOLOGY, INC Ops Cen Mgr (Bednar), Camarillo, CA
AMERICAN CONCRETE INSTITUTE Library, Detroit, MI
ARVID GRANT & ASSOC Olympia, WA
ATLANTIC RICHFIELD CO RE Smith, Dallas, TX
BATTELLE D Frink, Columbus, OH
BECHTEL CIVIL, INC Woolston, San Francisco, CA
BETHLEHEM STEEL CO Engrg Dept (Dismuke), Bethlehem, PA
BRITISH EMBASSY Sci & Tech Dept (Wilkins), Washington, DC
BROWN & ROOT Ward, Houston, TX
CANADA Viateur De Champlain, D.S.A., Matane, Canada
CHEVRON OIL FLD RSCH CO Strickland, La Habra, CA
CHILDS ENGRG CORP K.M. Childs, Jr, Medfield, MA
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COLLINS ENGRG, INC M Garlich, Chicago, IL
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EVALUATION ASSOC, INC MA Fedele, King of Prussia, PA
GRUMMAN AEROSPACE CORP Tech Info Ctr, Bethpage, NY
HALEY & ALDRICH, INC. T.C. Dunn, Cambridge, MA
HAYNES & ASSOC H. Haynes, PE, Oakland CA
HIRSCH & CO L Hirsch, San Diego, CA
HJ DEGENKOLB ASSOC W Murdough, San Francisco, CA
HUGHES AIRCRAFT CO Tech Doc Cen, El Segundo, CA
INTL MARITIME, INC D Walsh, San Pedro, CA
IRE-ITTD Input Proc Dir (R. Danford), Eagan, MN
JOHN J MC MULLEN ASSOC Library, New York, NY
LEO A DALY CO Honolulu, HI
LIN OFFSHORE ENGRG P. Chow, San Francisco CA
LINDA HALL LIBRARY Doc Dept, Kansas City, MO
MARATHON OIL CO Gamble, Houston, TX
MARITECH ENGRG Donoghue, Austin, TX
MC CLELLAND ENGRS, INC Library, Houston, TX
MOBIL R&D CORP Offshore Engrg Lib, Dallas, TX
EDWARD K NODA & ASSOC Honolulu, HI
NEW ZEALAND NZ Concrete Rsch Assoc, Library, Porirua
NUHN & ASSOC A C Nuhn, Wayzata, MN

PACIFIC MARINE TECH (M. Wagner) Duvall, WA
PILE BUCK, INC Smoot, Jupiter, FL
PMB ENGRG Coull, San Francisco, CA
PRESNELL ASSOC, INC DG Presnell, Jr, Louisville, KY
SANDIA LABS Library, Livermore, CA
SARGENT & HERKES, INC JP Pierce, Jr, New Orleans, LA
SAUDI ARABIA King Saud Univ, Rsch Cen, Riyadh
SEATECH CORP Peroni, Miami, FL
SHELL OIL CO E Doyle, Houston, TX
SIMPSON, GUMPERTZ & HEGER, INC E Hill, CE, Arlington, MA
TRW INC Crawford, Redondo Beach, CA; Dai, San Bernardino, CA; Engr Library, Cleveland, OH; Rodgers, Redondo Beach, CA
TUDOR ENGRG CO Ellegood, Phoenix, AZ
VSE Ocean Engrg Gp (Murton), Alexandria, VA
WESTINGHOUSE ELECTRIC CORP Library, Pittsburg, PA
WISS, JANNEY, ELSTNER, & ASSOC DW Pfeifer, Northbrook, IL
WOODWARD-CLYDE CONSULTANTS R Dominguez, Houston, TX; West Reg, Lib, Oakland, CA
BROWN, ROBERT University, AL
BULLOCK, TE La Canada, CA
CHAO, JC Houston, TX
CLARK, T. Redding, CA
GIORDANO, A.J. Sewell, NJ
HARDY, S.P. San Ramon, CA
HAYNES, B. No. Stonington, CT
HEUZE, F Alamo, CA
NIEDORODA, AW Gainesville, FL
PETERSEN, CAPT N.W. Pleasanton, CA
QUIRK, J Panama City, FL
SPIELVOGEL, L Wyncote, PA
STEVENS, TW Dayton, OH
ULASZEWSKI, CDR T.J. Honolulu, HI
VAN ALLEN, B Kingston, NY