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**Overview of Seismic Base Isolation Systems, Applications,
and Performance During Earthquakes**

**David J. Trummer
Stanley C. Sommer**

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OVERVIEW OF SEISMIC BASE ISOLATION SYSTEMS, APPLICATIONS, AND PERFORMANCE DURING EARTHQUAKES *

David J. Trummer and Stanley C. Sommer
Lawrence Livermore National Laboratory
P.O. Box 808, L-197
Livermore, California 94550

ABSTRACT

Seismic base isolation is a technique for mitigating the effects of earthquakes on structures. A structure is decoupled from the potentially damaging forces of an earthquake by placing a flexible isolation system between the structure and the ground. A database has been created for the U.S. Department of Energy which contains information about systems used to achieve seismic isolation, their applications in structures, and how they have performed during earthquakes. This paper will present an overview of the database.

INTRODUCTION

There are many U.S. Department of Energy (DOE) facilities which operate in areas of high seismic hazard. A potential method of reducing the effects of earthquakes on these facilities is seismic base isolation. In the United States, seismic base isolation has been used in new buildings, existing buildings, and large equipment. In order to apply seismic base isolation within the DOE, further technical development is needed to develop criteria for meeting DOE performance goals using base isolation.

As part of the technical development, a database has been created for the DOE which contains information about systems used to achieve seismic isolation, their applications in structures, and how the isolated structures have performed during earthquakes. The database is based on information contained in the Natural Phenomena Hazards Technology Center at the Lawrence Livermore National Laboratory (LLNL). Currently, the LLNL database includes information only on U.S. applications of seismic base isolation systems and the responses of the systems to U.S. earthquakes. The LLNL database will be expanded next year to include worldwide applications and system responses. Information in the database about the characteristics of the base isolation systems, on the other hand, is not limited to U.S. suppliers and fabricators since a system developed outside the U.S. could be implemented in a structure built in the U.S.

The LLNL database is not complete at this time and will evolve as the technology of base isolation evolves. Comments on the database are welcome to help make it more complete and to keep it current. One goal of developing the database is to make it useful for other organizations besides the DOE.

This paper gives an overview of the LLNL database. The tables in this paper are based on the database and provide information on base isolation systems, their applications, and their performance during earthquakes. The papers listed in the bibliography at the end of this paper are the sources of information for the LLNL database.

SEISMIC BASE ISOLATION SYSTEMS

Seismic base isolation can be achieved in many different ways. The basic elements of seismic isolation are flexible mounting systems that typically include some means of damping. These flexible devices shift the response of a structural system away from the peak response of an earthquake in order to limit the forces which can be generated in the supported structure. Damping is used with the devices to dissipate the ground motion energy and to limit the displacements of the flexible system to acceptable limits. An isolation system also provides rigidity under low lateral loads. Currently, the main types of flexible mounting systems are elastomeric bearings and friction sliders. These two systems are shown in Figures 1 and 2, respectively. This paper describes the following versions of the two types of seismic base isolation systems: lead rubber and high damping rubber elastomeric bearings, and the Friction Pendulum System which is a friction slider.

Elastomeric Bearing - Lead Rubber

The lead rubber elastomeric bearing is a block of laminated rubber with a cylindrical core of pure lead (see Figure 1). The laminated rubber consists of closely spaced horizontal steel plates that are bonded to the rubber during fabrication. These steel plates confine the lead plug and provide vertical stiffness to the bearing by inhibiting the rubber from bulging outwards. Under low horizontal displacement, the lead plug remains elastic and provides wind restraint with its high lateral stiffness. However, at

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large displacements, the lead yields to provide damping. This damping absorbs earthquake energy and helps control lateral displacements. Table 1 provides a list of performance issues and characteristics for lead rubber isolators.

Elastomeric Bearing - High Damping Rubber

The high damping rubber elastomeric bearing is geometrically similar to the lead rubber bearing, except that it does not have the lead plug (see Figure 1). The damping for the high damping rubber bearing is incorporated into the rubber with the appropriate compounds in the elastomeric matrix. Under low horizontal displacements, the rubber provides wind restraint with its high lateral stiffness. At design level horizontal displacements, the lateral stiffness reduces significantly. This results in lower frequency response of the isolated structure with the hysteretic damping absorbing the earthquake energy and limiting the lateral displacement. For displacements much greater than the design displacement, the horizontal stiffness of the bearing increases and this provides an ultimate restraint. Table 2 provides a list of performance issues and characteristics for high damping rubber isolators.

Friction Slider - Friction Pendulum System

The Friction Pendulum System (FPS) consists of a stainless steel, spherical, concave surface (see Figure 2). A stainless steel articulated slider surfaced with a low-friction composite bearing material slides on the concave surface. The FPS design is based on the principles of pendulum motion. Under low lateral loads, such as wind, the static (breakaway) coefficient of friction acts as fuse preventing lateral displacements. During lateral loads due to an earthquake, the articulated slider moves along the spherical surface, and raises the supported structure. The potential energy of the elevated structure provides the lateral restoring force that returns the structure to its original position. The earthquake energy is dissipated through hysteretic friction of the composite bearing material in contact with the concave spherical surface. Table 3 provides a list of performance issues and characteristics for the FPS isolators.

Figure 1. Elastomeric bearing.

Figure 2. Friction slider.

APPLICATIONS OF SEISMIC BASE ISOLATION SYSTEMS

Applications of seismic base isolation exist throughout the world. These applications include both new and retrofit installations in buildings and several nuclear power plants. Currently, there are over 65 approved base isolated buildings in Japan, while in the U.S. there are over 30. Other applications of base isolation are in bridges and equipment. The LLNL database is divided into U.S. applications of seismic base isolation systems in buildings and in non-buildings.

Seismic base isolation in the U.S. has become increasingly popular in recent years. In 1993, there are 16 new structures and 18 retrofit structures that have been completed or are in design or construction. Of these 34 structures, 27 are in California (12 new and 15 retrofit) and the remainder are in Utah, Oregon, and Nevada.

Government has played an important role in promoting the use of base isolation in the U.S. In 1989, the state of California enacted Senate Bill 920 which encouraged the State to be a leader in using new technology to mitigate the effects of earthquakes. Among the Bill's requirements were the selection by the State Architect of three state-owned buildings as demonstration projects, one being a new building and two being seismic retrofits. The new building slated as a demonstration project has yet to be selected, but a candidate is the Transportation Management Center that will be located in San Diego, CA. Only one of the two retrofit buildings has been identified and it is the State of California Justice Building in San Francisco, CA.

Table 4 lists applications of base isolation in the U.S. both for new and retrofit construction of buildings. Details about the isolation system, type of construction, total area, and engineering firms are included in the table. Of the 34 applications listed, 23 have an isolation system selected. The majority of these applications use the lead rubber bearings, high damping rubber bearings, or the FPS isolators discussed earlier in this paper.

New Buildings

As listed in Table 4, the first application of base isolation in new construction was the Foothill Communities

Law & Justice Center in 1985. Since that time, five additional new buildings have been completed, including the first hospital to be base isolated, the University of Southern California University Hospital in 1991. Another ten projects listed in Table 4 as new buildings are in various phases of design or construction. Included in Table 4 is the PRISM Advanced Liquid Metal Reactor which is a proposed DOE reactor for which a site has not been selected.

The function and size of new buildings with base isolation varies considerably. Building function ranges from hospitals that provide critical services to manufacturing facilities that house sensitive equipment. Sizes range from a 4,700 square foot residence to the 900,000 square foot, five building San Bernardino County Medical Center.

Retrofit Buildings

The first application of base isolation in retrofit construction was the Salt Lake City & County Building in 1988. Of the 18 retrofit structures listed in Table 4, four have been completed with the remainder in design or construction. Some of these buildings did not meet current seismic design requirements and in many cases were damaged by the 1989 Loma Prieta earthquake. The majority of the retrofit projects are in California and are for buildings of historical importance, such as the San Francisco City Hall and the U.S. Court of Appeals. Base isolation is used with historical buildings as an alternative to conventional strengthening and anchoring in order to preserve the architectural features of the building. The size of the retrofit projects vary from the 20,000 square foot Hawley Apartments to the 500,000 square foot San Francisco City Hall.

Non-Building Structures

There have been other applications of seismic isolation in the U.S. The concept of base isolation can be applied to non-buildings that need protection from seismic ground motions using similar design techniques as those which have been developed for buildings. Examples of the application of base isolation to non-buildings include bridges, storage tanks, art objects, and equipment. Table 5 lists some of these non-building applications. Not all of the non-building applications of base isolation in the U.S. are listed in Table 5. In particular, about ten base isolated bridges are not listed in the table. For bridges, they are isolated by placing an isolator between the tops of the columns and the bottom of the deck. The isolation system protects the columns, which are below the isolators, from the forces that would otherwise be generated by the bridge deck during an earthquake.

PERFORMANCE OF SEISMIC ISOLATION SYSTEMS DURING EARTHQUAKES

With the existence of many base isolation systems and the applications of those systems, it is of interest to review how the base isolation systems have performed during earthquakes. To date, no base isolated structure in the U.S.

has experienced an "ultimate" earthquake. However, a significant amount of data exists on the response of isolated structures to small and moderate sized earthquakes.

This paper covers the performance of U.S. buildings to earthquakes. Of the ten completed base isolated structures (six new and four retrofit), many have experienced earthquakes. Table 6 tabulates the performance of four buildings, the Foothill Communities Law and Justice Center (Bld=4), the Los Angeles County Fire Command and Control Center (Bld=10), the Rockwell Seal Beach Facility (Bld=19), and the University of Southern California University Hospital (Bld=31) (Bld refers to the building numbers listed in Table 4). All four buildings use elastomeric bearings as the base isolation system.

The Foothill Communities Law and Justice Center has experienced low level motions from seven earthquakes (Redlands, Palm Springs, Whittier, Upland, Sierra Madre, Landers, and Big Bear) since its completion in 1985. The horizontal accelerations recorded at the building foundation ranged from 0.02g to 0.14g. These low level accelerations were transmitted across the isolation system with essentially no reduction in magnitude, except for the Upland earthquake. During the Upland earthquake which had the largest acceleration of the seven earthquakes, the isolation system reduced the maximum acceleration from 0.14g to 0.05g. The other three buildings each experienced low level motions from the Sierra Madre, Landers, and Big Bear events.

The low level motions experienced at the four buildings resulted in some amplification of the accelerations from the basement of the building to the roof. Because the accelerations and lateral displacements were small, the elastomeric isolators responded with high lateral stiffness. As a result, the isolation system was only partially effective in limiting the accelerations transmitted to the superstructure. Therefore, the isolated building response was more like the response of a fixed based building with amplified accelerations at the roof level. No damage occurred in the buildings due to the small accelerations and displacements. The isolation systems become more effective in reducing the accelerations that are transmitted from the foundation to the basement as the ground motion increases. At design level displacements, the lateral stiffness of the isolation system is greatly reduced from its initial stiffness. This results in lower frequency response of the building.

SUMMARY

This paper presented information on seismic base isolation systems, their applications in buildings and non-buildings in the U.S., and the performance of isolated buildings to U.S. earthquakes. As the technology of seismic base isolation evolves, the LLNL database discussed in this paper will reflect that evolution. The current LLNL database can be used to make qualitative comparisons between various isolation systems. Additionally,

performance data such as earthquake response records can be used to validate analytical studies and to discover technical issues pertaining to the use of seismic base isolation in new and retrofit design.

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Table 1. Seismic base isolation systems - lead rubber isolators.

Performance Issue	Range*	Performance Characteristic
Design period (seconds)	1.5 - 3.0	Typically from 2 to 2.5 seconds
Effective damping (% of critical)	10 - 25	Provided by lead plug; helps control lateral building displacement; depends on nature of earthquake and supported structure
Effective lateral stiffness (kips/inch) - low horizontal displacement - design horizontal displacement	16 - 34	Slope of line from peak to peak force in a hysteresis loop - High initial elastic stiffness of lead plug provides wind restraint - Lead plug yields to provide damping that absorbs earthquake energy and helps control lateral displacements
Vertical stiffness (kips/inch)	3170 - 45100	High vertical stiffness provides vertical load capacity
Vertical load capacity of isolator (kips)	735 - 3307	Provided by steel plates
Vertical frequency (Hz)	12 - 20	High vertical stiffness results in high vertical frequency
Rubber diameter (inches) (Square isolator length)	16 - 63 (18 - 26)	Determined by diameter of steel plates that provide vertical load capacity; related to bearing stability
Rubber total thickness (inches)	3.5 - 9.5	Provides lateral flexibility; number of rubber layers times the rubber layer thickness
Lead plug diameter (inches)	1 - 11	Lead plug provides damping to absorb earthquake energy and to limit lateral displacements
Isolator total height (inches)	9 - 26	May be a clearance issue in retrofit applications
Connection detail	-	Dowelled or bolted, with bolted being most common
Materials	-	Rubber provides lateral flexibility Steel plates provide vertical load capacity and confine the lead plug Lead plug provides wind resistance and reduces earthquake forces and displacements with energy dissipation
Environmental protection	-	Cover layer of rubber protects steel plates
Suppliers / fabricators	Dynamic Isolation Systems, Inc. (U.S. license) Oiles Industries, Ltd. (Japan license)	FURON - Structural Bearing Division LTV Energy Products Company Bridgestone Corporation

* values from literature contained in the Natural Phenomena Hazards Technology Center at LLNL

Table 2. Seismic base isolation systems - high damping rubber isolators.

Performance Issue	Range*	Performance Characteristic
Design period (seconds)	1.2 - 3.5	Typically around 2 seconds
Effective damping (% of critical)	8 - 30	Characteristic of the rubber compound; helps control lateral building displacement
Effective stiffness (kips/inch) - low horizontal displacement - design horizontal displacement - high horizontal displacement	3 - 36	Slope of line from the peak to peak force in a hysteresis loop - stiffness is high and provides wind restraint - stiffness much lower for seismic loading at design levels - stiffness is high, increasing frequency of isolated structure
Vertical stiffness (kips/inch)	1470 - 45100	High vertical stiffness provides vertical load capacity
Vertical load capacity of isolator (kips)	45 - 1740	Provided by steel plates
Vertical frequency (Hz)	9.1 - 29.5	High vertical stiffness results in high vertical frequency
Rubber diameter (inches)	9.7 - 55.9	Determined by diameter of steel plates that provide vertical load capacity; related to bearing stability
Rubber total thickness (inches)	1.7 - 11.4	Provides lateral flexibility; number of rubber layers times the rubber layer thickness
Isolator total height (inches)	8 - 24	May be a clearance issue in retrofit applications
Connection detail	-	Dowelled or bolted, with bolted being most common
Material	-	<i>Rubber</i> provides lateral flexibility and damping <i>Steel plates</i> provide vertical load capacity and confine the lead plug
Environmental protection	-	Cover layer of rubber protects steel plates
Suppliers / fabricators	LTV Energy Products Company Bridgestone Corporation Dynamic Isolation Systems, Inc. Fyfe Associates	FURON - Structural Bearing Division Malaysian Rubber Producers' Research Assoc. Rubber Consultants of England Dynamic Rubber, Inc.

* values from literature contained in the Natural Phenomena Hazards Technology Center at LLNL

Table 3. Seismic base isolation systems - friction pendulum system isolators.

Performance Issue	Range*	Performance Characteristic
Design period (seconds)	1.3 - 3.5	Determined using pendulum equation, $T=2\pi\sqrt{r/g}$, which is independent of the building weight; function of radius of curvature, r , of spherical surface (g = acceleration of gravity)
Design damping (% of critical)	15 - 30	Provided by hysteretic friction; helps control lateral building displacement
Radius of curvature of concave surface (inches)	39 - 88	Determines period of system
Lateral restoring stiffness (kips/inch)	0.1 - 27	Directly proportional to the supported weight ($k=W/r$)
Static (breakaway) coefficient of friction (%)	-	Acts as fuse for wind loads
Dynamic (sliding) coefficient of friction (%)	5 - 10	Increasing the coefficient lowers the displacement; used to control lateral building displacement
Vertical load capacity of isolator (kips)	4 - 5000	Determined by diameter of articulated slider
Stick-slip condition	-	Uniform contact pressure between concave surface and semi-spherical slider reduces high frequency stick-slip motions
Isolator diameter (inches)	20 - 42	Any diameter to accommodate required seismic displacement
Isolator total height (inches)	6 - 12	Small variation in height relative to supported loads; isolation period independent of height
Materials	-	<i>Stainless steel</i> concave surface and articulated slider <i>Composite bearing material</i> provides high load capacity and low friction
Environmental protection	-	Circular retainer with seal; spherical concave surface faced downward for dust protection
Suppliers / fabricators	-	Earthquake Protection Systems, Inc. VSL Corporation

* values from literature contained in the Natural Phenomena Hazards Technology Center at LLNL

Table 4. Applications of seismic base isolation to buildings in the U.S. (Key to abbreviations listed after Table 5).

Bld	Application	Location	Type	Isolation	Status	Iso	Owner	Sty
1	Channing House Retirement Home	Palo Alto, CA	retrofit	LR	design	113	Channing House	
2	Educational Services Center	Los Angeles, CA	retrofit	EBS	construction		L.A. Community College District	9
3	Evans & Sutherland Building 600	Salt Lake City, UT	new	LR	completed - 1988	98	Evans & Sutherland, Corporation	4
4	Foothill Comm. Law & Justice Center	Rancho Cucamonga, CA	new	HDR	completed - 1985	98	County of San Bernardino	5
5	Hawley Apartments	San Francisco, CA	retrofit	FPS	completed - 1991	31	Dr. Hawley	4
6	Hayward City Hall	Hayward, CA	retrofit	HDR & FPS	design	36	City of Hayward	11
7	Kaiser Data Proces. & Telecomm. Cent.	Corona, CA	new	LR & HDR	completed - 1992		Kaiser Foundation Health Plan	2
8	Kerckhoff Hall, UCLA	Los Angeles, CA	retrofit	LR	construction		Regents of University of California	6
9	LA County Emerg. Operations Center	East Los Angeles, CA	new	HDR	construction		County of Los Angeles	
10	LAC Fire Command & Control Facil.	East Los Angeles, CA	new	HDR	completed - 1990	32	County of Los Angeles	2
11	LAC & USC Diagn. & Treatment Build.	Los Angeles, CA	new		design			6
12	Loma Linda Hospital	Loma Linda, CA	new		design		Veteran's Administration	
13	Long Beach Hospital	Long Beach, CA	retrofit	LR & PTFE	design	156	Veteran's Administration	12
14	Mackay School of Mines	Reno, NV	retrofit	HDR & PTFE	completed - 1993	106	University of Nevada Reno	3
15	ML King-CR Drew Diagn. Trauma Cent.	Watts, CA	new	HDR & BAS	design		County of Los Angeles	
16	Masonic Hall	San Francisco, CA	retrofit		stopped			
17	Oakland City Hall	Oakland, CA	retrofit	LR	construction	100	City of Oakland	18
18	PRISM Advanced Liquid Metal Reactor		new		design		General Electric	
19	Rockwell Seal Beach Facility	Seal Beach, CA	retrofit	LR	completed - 1991	78	Rockwell International	8
20	Salt Lake City & County Building	Salt Lake City, UT	retrofit	LR	completed - 1988	447	Salt Lake City Corporation	5
21	Salt Lake City Medical Building	Salt Lake City, UT	new		design			
22	San Bernardino County Medical Center	Colton, CA	new	HDR	design		County of San Bernardino	
23	San Francisco Asian Art Museum	San Francisco, CA	retrofit		design	200	City & County of San Francisco	3
24	San Francisco City Hall	San Francisco, CA	retrofit		design		City & County of San Francisco	
25	San Francisco Main Public Library	San Francisco, CA	new	LR	construction		City & County of San Francisco	7
26	State of California Justice Building	San Francisco, CA	retrofit	HDR	design	170	State of California	6
27	Tandem Computers Manufacturing Facil	San Jose, CA	new		stopped		Tandem Computers	4
28	50 United Nations Plaza	San Francisco, CA	retrofit		design		US General Services Administration	6
29	U.S. Court of Appeals	San Francisco, CA	retrofit	FPS	construction	248	US General Services Administration	4
30	U.S. Customs House	San Francisco, CA	retrofit		design	300	US General Services Administration	5
31	USC University Hospital	Los Angeles, CA	new	LR & HDR	completed - 1991	149	National Medical Enterprises & USC	8
32	Utah State Capitol Building	Salt Lake City, UT	retrofit		design			
33	Water Control Cent.-Water Quality Lab.	Portland, OR	new	LR	design	35	Portland Water Bureau	2
34	West Los Angeles Residences	West Los Angeles, CA	new	GERB	completed - 1992		David Lowe	

Table 4 cont'd. Applications of seismic base isolation to buildings in the U.S. (Key to abbreviations listed after Table 5).

Bid	Superstructure Characteristics	Area	Cost	Structural and Isolation Engineers	Supplier
1	1962 R/C moment frame & shear wall	260000		Rinnie & Peterson / Dynamic Isolation Systems	Dynamic Isolation Systems
2	1961 concrete frame	90000	\$1,013,000	Fleming Corporation	
3	steel moment frame	160000	\$8,000,000	Reavely Engin. & Assoc. / Dynamic Isolation Syst.	Dynamic Isolation Systems/Furon
4	braced steel frame & concrete basement	230000	\$36,000,000	Taylor & Gaines / Reid & Tarics	Oil States Industries (LTV)
5	1920 wood bearing wall	20000		Earthquake Protection Syst.	Earthquake Protection Systems/VSL
6	1969 nonductile R/C moment frame	145000	\$7,000,000	EQE - San Francisco / Charles Kircher & Assoc.	Earthq. Protect. Syst. & Bridgest.
7	1968 K braces with concrete walls	120000	\$32,000,000	Taylor & Gaines / Englekirk, Hart, and Sabol	Dynamic Isolation Systems/Furon
8	1929 pour-in place concr. & hollow tile	100000	\$15,300,000	Brandow & Johnston / The Hart Group	Dynamic Isolation Systems/Furon
9		33000	\$6,000,000	DMJM	Bridgestone Corporation
10	perimeter braced steel frame	32000	\$6,300,000	Fluor Daniel Engineers	Fyfe Associates/Dynamic Rubber
11	moment resisting steel frame	400000		KPFF Engineers	
12			\$80,000,000		
13	1967 R/C perforated shear wall	350000		A.C. Martin & Associates / Dynamic Isolation Syst.	Dynamic Isolation Systems/Furon
14	1908 unreinforced mason. bearing wall	50000	\$7,000,000	Jack Howard & Associates / Base Isolation Consult.	Furon
15		140000	\$40,000,000	John Martin / Base Isolation Consultants	Dynamic Isolation Systems/Furon
16	1912 building		\$2,391,049		
17	1914 steel frame & unreinf. masonry	153000	\$76,800,000	Forell-Elsesser Engineers / Dynamic Isolation Syst.	Dynamic Isolation Systems
18					
19	1967 nonductile R/C moment frame	300000	\$14,000,000	Englekirk & Hart	Dynamic Isolation Systems/Furon
20	1894 unreinforced mason. bearing wall	170000	\$30,000,000	E.W. Allen / Forell-Elsesser Engineers	Dynamic Isolation Systems/LTV
21			\$20,000,000	Reid & Tarics	
22	5 separate structures	900000	\$500,000,000	KPFF Engineers / Taylor & Gaines	Dynamic Isolation Systems
23	1916 steel frame & unreinf. masonry	170000		Rutherford & Chekene / Charles Kircher & Assoc.	
24	steel moment frame	500000	\$100,000,000	Forell-Elsesser Engineers	
25	steel moment frame on mat slab	377000	\$87,000,000	Olm Structural Design / Forell-Elsesser Engineers	Dynamic Isolation Systems
26	1919 steel frame & unreinf. masonry	252000	\$40,000,000	Rutherford & Chekene / Charles Kircher & Assoc.	Bridgestone Corporation
27	braced steel frame			Forell-Elsesser / Dynamic Isolation Systems	
28	1936 concr. & steel frame with mason.	345000		H.J. Degenkolb Associates	
29	1905 steel frame & unreinf. masonry	350000		Skidmore, Owings, Merrill	Earthquake Protection Systems/VSL
30	1911 steel frame & unreinforced mason.	142000	\$14,000,000	URS Blume	
31	perimeter braced steel frame	350000	\$50,000,000	KPFF Engineers	Dynamic Isolation Systems/Furon
32					
33	moment frame	28000		Harris Group / Dynamic Isolation Systems	Dynamic Isolation Systems
34		4700	\$20,000	David Lowe	GERB

Table 5. Some applications of seismic base isolation to non-buildings in the U.S.

Application	Location	Type	Sys	Superstructure	Iso	Status	Owner
All American Canal Bridge	Imperial, CA	retrofit	LR	1960 bridge - 3 spans	12	completed - 1987	Caltrans
Art Objects at J.P. Getty Museum	Malibu, CA					completed - 1991	
Beverly Park Elevated Water Tank	Seattle, WA	retrofit		1959 tank - welded & 18000 kips		design	
Bridges B764E&W	Verdi, NV	retrofit	LR	1950 bridge - 7 span steel girder & bent		construction	Nevada DOT
Circuit Breakers	CA	new	HDR			completed - 1977	CA Dept. of Water Res.
Clackamas Connector	Portland, OR	new	LR	bridge - 8 span cont. conc. box girder		construction	Oregon DOT
Eel River Bridge	Rio Dell, CA	retrofit	LR	1941 bridge - 2 span steel truss	12	completed - 1987	Caltrans
I.S.P. Ammonia Storage Tanks	Calvert City, Ky	retrofit	FPS	steel tank - 450000 lbs, 12 ft. x 60 ft.	4	completed - 1993	Inter. Specialty Product
Liquid Argon Calorimeter	Stanford, CA	new	LR			completed	SLAC
Main Yard Vehicle Access Bridge	Los Angeles, CA	retrofit	LR	1954 bridge - 2 span	8	completed - 1987	LAC Trans. Com.
Maple Leaf Elevated Water Tank	Seattle, WA	retrofit		1949 tank - riveted & 9000 kips		design	
Mark II Detector Unit	Stanford, CA	new	LR	3.2 million lbs. & 30 feet tall	4	completed - 1987	SLAC
Mobile Excitors	Diablo Canyon, CA	new				completed	Pacific Gas & Electric
Olympic Boulevard Bridge	Walnut Creek, CA	new	LR	bridge - 4 span cont. composite steel gir.		construction	Caltrans
Pittsburgh Emergency Water Tank	Pittsburgh, CA	new	FPS			completed - 1988	DOW Chem. Company
Poplar Street Bridge, East Appro.	St. Louis, MO	retrofit	LR	1966 bridge	128	completed - 1990	Illinois DOT
Santa Ana River Bridge	Riverside, CA	retrofit	LR	1936 bridge - 13 span steel truss & gir.	28	completed - 1986	Metro. Water Distr.
Sierra Point Overhead	San Francisco, CA	retrofit	LR	1957 bridge - 10 span concrete & steel	36	completed - 1985	Caltrans
Sexton Creek Bridge	Sexton, IL	new	LR	bridge - 3 span cont. steel plate gir.		completed	Illinois DOT
Squamscott River Bridge	Exeter, NH	new	LR	bridge - 6 span cont. composite steel gir.		construction	New Hampshire DOT
S.W. Myrtle #2 Elev. Water Tank	Seattle, WA	retrofit		1949 tank - riveted & 9087 kips		design	
Titan Solid Rocket Motor Storage	Vandenberg, CA	new	HDR			completed - 1992	U.S. Air Force

Key to Abbreviations in Tables 4 and 5:

Bld = building number
 Iso = number of isolators
 Sty = number of stories
 Area = area in square feet
 LR = lead rubber bearings
 EBS = Earthquake Barrier System isolation

HDR = high damping rubber bearings
 FPS = Friction Pendulum System
 PTFE = polytetrafluoroethylene (Teflon)
 BAS = bronze alloy sliders
 R/C = reinforced concrete
 Sys = isolation system

Table 6. Performance of base isolated structures to U.S. earthquakes.

Bld/Event	Date	Mag	Dist (km)	Period Trans (sec)	Period Long (sec)	Period Trans (sec)	Period Long (sec)	Period Trans (sec)	Period Long (sec)	Period Event (sec)	MAcc Horz (g)	MAcc Horz (g)	MAcc Found (g)	MAcc Horz (g)	MAcc Horz (g)	MAcc Base (g)	MAcc Roof (g)	Ampf Horz %	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)	RelDs Trans (cm)		
4 Redlands	2-Oct-85	4.8	30	0.57	0.61	2.00	2.00	2.00	2.00	-	0.05	0.03	0.02	0.03	0.03	0.02	0.03	50	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 Palm Springs	8-Jul-86	5.9	90	0.57	0.61	2.00	2.00	2.00	2.00	-	0.02	0.02	0.02	0.05	0.05	0.02	0.05	150	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 Whittier	1-Oct-87	5.9	47	0.57	0.61	2.00	2.00	2.00	2.00	-	0.05	0.03	0.03	0.06	0.06	0.03	0.06	100	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 Upland	28-Feb-90	5.5	12	0.57	0.61	2.00	2.00	2.00	2.00	0.75	0.24	0.14	0.05	0.16	0.16	0.05	0.16	220	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 Sierra Madre	28-Jun-91	5.8	43	0.57	0.61	2.00	2.00	2.00	2.00	0.85	0.04	0.03	0.04	0.08	0.08	0.04	0.08	100	-	-	-	-	-	-	-	-	-	-	-	-	-	
4 Landers	28-Jun-92	7.5	106	0.57	0.61	2.00	2.00	2.00	2.00	0.73	0.12	0.11	0.10	0.19	0.19	0.10	0.19	90	1.38	-	0.48	-	-	-	-	-	-	-	-	-	-	1.51
4 Big Bear	28-Jun-92	6.6	70	0.57	0.61	2.00	2.00	2.00	2.00	-	0.04	0.06	0.05	0.07	0.07	0.05	0.07	40	-	-	-	-	-	-	-	-	-	-	-	-	-	
10 Sierra Madre	28-Jun-91	5.8	28	0.36	0.32	2.17	2.17	2.17	2.17	0.91	0.12	0.18	0.09	0.11	0.11	0.09	0.11	22	-	-	-	-	-	-	-	-	-	-	-	-	-	
10 Landers	28-Jun-92	7.5	161	0.36	0.32	2.17	2.17	2.17	2.17	0.96	0.05	0.05	0.05	0.12	0.12	0.08	0.12	50	-	1.62	0.11	-	-	-	-	-	-	-	-	-	0.14	
10 Big Bear	28-Jun-92	6.6	125	0.36	0.32	2.17	2.17	2.17	2.17	-	-	-	0.05	0.05	0.05	0.05	0.05	0	-	-	-	-	-	-	-	-	-	-	-	-	-	
19 Sierra Madre	28-Jun-91	5.8	57	1.10	1.10	2.75	2.75	2.75	2.75	-	-	-	0.02	0.02	0.03	0.03	0.03	50	-	-	-	-	-	-	-	-	-	-	-	-	-	
19 Landers	28-Jun-92	7.5	160	1.10	1.10	2.75	2.75	2.75	2.75	1.48	-	-	0.04	0.09	0.09	0.09	0.09	0	-	1.52	0.10	-	-	-	-	-	-	-	-	-	2.19	
19 Big Bear	28-Jun-92	6.6	126	1.10	1.10	2.75	2.75	2.75	2.75	-	-	-	0.04	0.05	0.08	0.08	0.08	60	-	-	-	-	-	-	-	-	-	-	-	-	-	
31 Sierra Madre	28-Jun-91	5.8	29	1.00	1.00	2.21	2.21	2.21	2.30	1.00	0.16	0.09	0.05	0.09	0.09	0.05	0.09	80	-	-	-	-	-	-	-	-	-	-	-	-	-	
31 Landers	28-Jun-92	7.5	163	1.00	1.00	2.21	2.21	2.21	2.30	1.28	0.05	0.04	0.09	0.09	0.09	0.09	0.09	0	0.83	-	-	-	-	-	-	-	-	-	-	-	0.61	
31 Big Bear	28-Jun-92	6.6	127	1.00	1.00	2.21	2.21	2.21	2.30	-	-	-	0.05	0.03	0.06	0.06	0.06	100	-	-	-	-	-	-	-	-	-	-	-	-	-	

Key to Abbreviations in Table 6:

Bld = building number from Table 4
 Bld 1 = Foothill Communities Law and Justice Center
 Bld 10 = Los Angeles County Fire Command and Control Center
 Bld 19 = Rockwell Seal Beach Facility
 Bld 31 = University of Southern California University Hospital
 Mag = magnitude of earthquake
 Dist = distance from the earthquake epicenter
 Trans = transverse direction
 Long = longitudinal direction
 Fixed = fixed base structure
 Isol = base isolated structure
 Event = seismic event

MAcc = maximum acceleration
 Horz = horizontal direction
 FreeF = free field
 Found = foundation (below isolation system)
 Base = base (above isolation system)
 Fr = floor
 Ampf = amplification of roof displacement relative to basement displacement
 RelDs = [(roof-base) / base] x 100
 RelDs = relative displacement
 For Base: displacement relative to ground
 For 1st Fr, 2nd Fr, 4th Fr, and Roof: displacement relative to basement

END

**DATE
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11/10/93