SYSTEM IDENTIFICATION OF BASE-ISOLATED BUILDINGS UTILIZING RECORDS FROM RECENT SOUTHERN CALIFORNIA EARTHQUAKES

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ABSTRACT

System identification is used in this study as a systematic approach to determine modal periods, mode shapes, and estimated damping for three Southern California base-isolated buildings. In addition, estimates of the level of response each building experienced during recent earthquakes can be evaluated. Of particular interest are the variations in modal parameters as a function of the level of excitation due to the non-linear nature of these structures.

By using identification of each building for several earthquakes and dividing the time histories into short segments, structural response trends can be investigated.

It is shown that structural period and damping vary with amplitude of excitation. Since the bearings are hysteretic and softening elements, under increased structural response, the periods of vibration as well as the equivalent modal viscous damping increase. It is also shown that although the 1994 Northridge California earthquake generated moderate levels of horizontal ground acceleration at building sites, the bearings were exercised well below their maximum design levels.

KEYWORDS

system identification; seismic isolation; base isolation; Northridge earthquake; Landers earthquake; modal periods; mode shapes; modal damping

INTRODUCTION

System identification is used in this study as a systematic approach to determine modal periods, mode shapes, and estimated damping for three Southern California base-isolated buildings. In addition, estimates of the level of response each building experienced during recent earthquakes are evaluated.

The three Southern California buildings considered in this study are the Foothill Communities Law and Justice Center (FCLJC), located in Rancho Cucamonga, San Bernardino County; the Los Angeles Fire Command and Control Facility (FCCF), located in Los Angeles County; and the University of Southern California University Hospital (USCUH), also located in Los Angeles County.

The computer program MODE-ID, developed by Beck [1978], and later extended to handle multiple inputs and outputs by Werner, Beck, and Levine [1987], has been utilized to determine the best-fit equivalent linear properties for each of the buildings. For each direction, a single input (recorded foundation acceleration) and multiple outputs (recorded structural accelerations) were used to determine the best-fit modal periods, damping, participation factors, and mode shapes. Table 1 lists the recent Southern California earthquakes used for identification of the three buildings and some pertinent peak acceleration data.

Table 1 Summary of earthquakes, epicentral distances, and peak accelerations for the three studied buildings in Southern California.

EARTHQUAKE		**FCLJC**		**FCCF**		**USCUH**	
		Epicentral Distance (km)	Accel. F,B,R * (% of g.)	Epicentral Distance (km)	Accel. F,B,R * (% of g.)	Epicentral Distance (km)	Accel. F,B,R * (% of g.)
1985 Redlands	M_L 4.8	30	4, 1, 3				
1986 Palm Springs	M_L 5.9	90	2, 2, 4				
1987 Whittier	M_L 6.1	47	3, 3, 6				
1990 Upland	M_L 5.5	12	14, 5, 16				
1991 Sierra Madre	M_L 5.8			28	8, 9, 11		
1992 Landers	M_S 7.5	106	11, 9, 19	161	5, 8, 12	163	4, 4, 9
1994 Northridge	M_W 6.7	90	5, 5, 9	38	22, 35, 32	36	37, 13, 21

* F, B, R represents peak horizontal acceleration at the Foundation (below isolators), Base (above the isolators), and Roof.

BASE-ISOLATED BUILDINGS

The Foothill Communities Law and Justice Center (FCLJC) was built in 1985 and consists of a basement level, a ground floor, second through fourth floors, and roof. The FCLJC is owned by the County of San Bernardino, and is utilized as a courthouse, legal center, and houses other government offices. The isolation level, consisting of 98 high damping rubber bearings, is below the basement, with substantial retaining walls all around and an isolation gap of 40.6 cm between the wall and the structure. The structure is a steel braced frame building from the first floor to the roof, with concrete shear walls from the basement to the first floor. A schematic diagram of this building showing the locations of the strong motion transducers is contained in CSMIP [1995b]. For additional details regarding this structure refer to Kelly and Celebi [1984], Kelly *et al.* [1991], or Maison and Ventura [1992].

The Los Angeles County Fire Command and Control Facility (FCCF) was built in 1989 and consists of a ground level, a second floor, and a roof. The FCCF is owned by the County of Los Angeles, and is utilized as the emergency 911 dispatch center for the county and administered by the fire department. The isolation level is just below the ground level. The structure is a steel braced frame with each of the 32 wide-flange steel columns mounted on a high-damping rubber isolator. The 20 perimeter isolators contain a slack chain in the center of the unit that acts as a displacement restraint for the building should the horizontal bearing displacements exceed 32 cm [Anderson, 1990]. A schematic diagram of this building showing the locations of the strong motion transducers is contained in CSMIP [1995a]. For additional details regarding this structure, refer to Anderson [1990], Bachman *et al.* [1990], or Anderson *et al.* [1992].

The University of Southern California University Hospital (USCUH) was also built in 1989 and consists of a basement level, first through seventh floors, a roof, and a penthouse. The USCUH is owned by National Medical Enterprises. The isolation level is below the basement with retaining walls surrounding the structure outside of the 33.7 cm isolation gap. The structure is a steel braced frame building mounted on a total of 149 isolating bearings: 68 lead / rubber isolators at the perimeter of the building and 81 elastomeric isolators at remaining columns. A schematic diagram of this building showing the locations of the strong motion transducers is contained in CSMIP [1994d]. For additional details regarding this structure, refer to Asher *et al.* [1990].

System identification work has been done for these structures in other studies, such as Huang *et al.* [1993], Kelly *et al.* [1991], and Nagarajaiah and Xiahong [1995].

SYSTEM IDENTIFICATION RESULTS AND DISCUSSION

Foothill Communities Law and Justice Center (FCLJC)

The FCLJC was instrumented by the California Division of Mines and Geology (CDMG), Strong Motion Instrumentation Program (CSMIP), in 1985. The records which have been utilized for this study are from the 1985 Redlands [Huang *et al.*, 1986], the 1986 Palm Springs [CSMIP, 1991], the 1987 Whittier [CSMIP, 1993a], the 1990 Upland [Huang *et al.*, 1990], the 1992 Landers [CSMIP, 1993b], and the 1994 Northridge [CSMIP, 1995b] earthquakes. Table 2 shows the identified equivalent linear periods and damping for the first five modes using MODE-ID. The recorded time histories have been divided into ten-second segments and the identification performed in each segment to demonstrate the variations in the identified properties as the amplitudes of the excitation and of the response change. Also given are values for the fixed-base period determined by computer model.

Table 2 FCLJC identified model periods and equivalent viscous damping values.

EARTHQUAKE		Transverse				Longitudinal				Torsional	
		Mode 1		Mode 2		Mode 1		Mode 2		Mode 1	
	Time Segment (sec)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)
1985 Redlands	0 - 10	0.61	4.3	0.28	9.9	0.61	7.5	0.27	7.5		
	10 - 20	0.60	4.6	0.26	13.0	0.60	3.8	0.27	4.9		
1986 Palm Springs	0 - 10	0.63	8.2	0.30	12.0	0.60	6.0	0.28	9.1		
	10 - 20	0.65	4.8	0.30	11.1	0.65	6.3	0.29	6.5		
	20 - 30	0.64	6.5	0.31	10.0	0.65	5.6	0.29	4.7		
	30 - 40	0.63	4.4	0.32	12.6	0.62	6.0	0.27	9.8		
1987 Whittier	0 - 10	0.65	4.6	0.29	9.1	0.66	5.1	0.29	5.4		
	10 - 20	0.63	5.1	0.31	12.3	0.66	6.9	0.30	6.7		
	20 - 30	0.64	5.5	0.28	8.3	0.65	6.7	0.29	7.3		
	30 - 40	0.61	6.0	0.27	7.4	0.62	5.8	0.28	6.6		
1990 Upland	0 - 10	0.79	6.9	0.36	12.9	0.80	6.3	0.33	8.5	0.80	11.0
	10 - 20	0.76	7.3	0.34	17.3	0.76	5.2	0.32	7.8	0.73	4.1
	20 - 30	0.71	6.5	0.33	17.1	0.71	5.7	0.31	6.8	0.72	0.1
	30 - 40	0.69	7.3	0.28	9.5	0.69	4.8	0.28	6.1	0.65	13.0
1992 Landers	0 - 10	0.69	4.5	0.29	11.2	0.71	8.2	0.29	6.6	0.67	5.1
	10 - 20	0.77	6.6	0.33	13.7	0.78	7.2	0.33	11.0	0.75	2.1
	20 - 30	1.03	19.0	0.40	9.9	0.96	20.5	0.38	14.2	--	--
	30 - 40	1.04	25.6	0.39	3.7	1.04	20.1	0.45	--	0.89	14.0
	40 - 50	0.86	16.7	0.39	4.4	0.84	13.2	0.36	9.6	0.90	15.0
	50 - 60	0.79	8.2	0.34	13.9	0.79	8.6	0.35	9.0	0.79	4.1
1994 Northridge	0 - 10	0.69	5.4	0.31	15.7	0.73	4.9	0.31	8.7	0.65	0.6
	10 - 20	0.78	8.7	0.36	13.5	0.83	9.4	0.36	9.7	0.81	2.7
	20 - 30	0.76	4.9	0.33	8.1	0.79	6.8	0.34	8.7	0.74	3.1
	30 - 40	0.75	4.7	0.36	14.2	0.76	6.9	0.32	6.1	0.74	3.4
	40 - 50	0.71	5.1	0.29	10.5	0.71	8.7	0.29	7.1	0.70	1.7
	50 - 60	0.71	4.4	--	--	0.74	5.9	0.29	8.4	0.64	4.4
Fixed Base [Halling, 1995]		0.62				0.72				0.51	

The foundation motions from the Landers and Northridge earthquakes' transverse (channel 12 acceleration) and longitudinal (channel 16 acceleration) directions are shown in figure 1. The largest amplitudes occur in the 20-40 sec and the 10-20 sec segments in the Landers and Northridge earthquakes, respectively. The peak acceleration values occur in the 20-30 sec segment, however, for both channels the velocity and displacement (more representative of longer period motion) are large in the 30-40 sec segment as well. In fact, the peak velocity and displacement in channel 16 occur in the 30-40 sec segment. The system identification for these earthquakes clearly shows the connection between the length of the periods of vibration and the intensity of shaking, a result of the non-linearity of the isolators, even at these low amplitudes of vibration. This trend is even evident for the small earthquakes: Redlands, Whittier, and Upland, (strongest motion in the 0-10 sec segment), and Palm Springs (strongest in 10-20 sec segment).

For the Palm Springs, Landers, and Northridge earthquakes, which have significantly larger epicentral distances (see table 1), the first modal periods in both directions lengthen, and then shorten again at the end of the record. Also of note is the modal damping for the transverse and longitudinal directions first mode during the Landers event. The damping increases to 25.6% and 20.5% of critical damping in the transverse and longitudinal directions, respectively, and then decreases. For the small-strain range, the equivalent viscous damping for the isolators actually can get quite large, possibly into this range. This increasing trend is similar for the Northridge earthquake, although not nearly as marked. Figure 2 shows the identified first transverse and longitudinal mode shapes from segments of the time histories corresponding to lesser and greater response levels. As the amplitude of the response increases (i.e., Landers 30-40 sec and Northridge 10-20 sec), the displacement across the isolator bearings becomes a larger portion of the first modal response.

Los Angeles County Fire Command and Control Facility (FCCF)

The FCCF was instrumented by CDMG in 1989. The records that have been used here are those from the preliminary releases of the 1991 Sierra Madre [CSMIP, 1994a], the 1992 Landers [CSMIP, 1994b], and the 1994 Northridge [CSMIP, 1995a] earthquakes. Table 3 shows the identified equivalent linear periods and damping for the first three modes using MODE-ID. The identification is again performed in ten-second segments.

Table 3 FCCF identified model periods and equivalent viscous damping values

EARTHQUAKE		**Transverse**				**Longitudinal**				**Torsional**	
		Mode 1		Mode 2		Mode 1		Mode 2		Mode 1	
	Time Segment (sec)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)
1991 Sierra Madre	0 - 10	0.77	32.5			0.85	20.5			0.82	-1.7
	10 - 20	0.69	23.4			0.81	21.8			0.75	--
	20 - 30	0.61	21.4			0.63	23.1			0.52	6.7
	30 - 40	0.56	22.2			0.55	25.0			0.46	24.
	40 - 50	0.46	37.7			0.45	27.6			0.36	37.
	50 - 60	0.34	20.3			0.36	20.0			0.36	34.
1992 Landers	0 - 10	0.47	24.7			0.47	24.3			0.40	23.
	10 - 20	0.53	14.7			0.54	11.2			0.46	4.5
	20 - 30	0.90	21.1			0.92	19.8			0.85	2.6
	30 - 40	1.06	17.3			1.01	15.8			1.00	7.2
	40 - 50	1.05	19.8			0.99	20.9			0.89	9.3
	50 - 60	0.91	22.7			0.87	21.6			0.79	24.
	60 - 70	0.80	21.7			0.76	21.1			0.70	21.
	70 - 80	0.77	24.1			0.73	22.4			0.66	24.
	80 - 90	0.67	32.5			0.66	28.1			0.57	21.
	90 - 100	0.63	35.7			0.60	27.3			0.54	--

	100 - 106	0.62	32.1	0.55	26.3	0.39	32.
1994 Northridge	0 - 10	0.55	9.0	0.55	16.2	0.49	-0.1
	10 - 20	1.30	24.8	1.21	22.5	0.81	12.4
	20 - 30	1.23	21.2	1.13	18.9	1.01	21.5
	30 - 40	1.00	25.5	1.03	29.3	0.78	22.9
	40 - 50	0.81	22.7	0.84	23.7	0.68	21.2
	50 - 60	0.71	23.6	0.72	23.4	0.62	20.6
Fixed Base [Halling, 1995]		0.42		0.38		0.23	

The foundation motions from the Landers and Northridge transverse (channel 6 acceleration) and longitudinal (channel 5 acceleration) directions are shown in figure 1. The most intense shaking occurs in the 30-40 sec, and 10-20 sec segment, respectively. The Sierra Madre record contains the largest amplitude motion in its first ten seconds. For these earthquakes, the first modal period for each direction significantly lengthens during the largest amplitude motions. However, the damping, which is very large, does not seem to follow a recognizable trend. Several segments indicate negative damping in the torsional mode which may be the result of transverse excitation contributing to the torsional response of the structure. This is noteworthy, since the FCCF has an extremely symmetrical lateral resistance system. During the Northridge earthquake, impact of the building with a grouted tile entrance walkway produced acceleration spikes which may have adversely affected the system identification. Figure 2 shows the identified first transverse and longitudinal mode shapes from segments of the time histories. As the amplitude of the response increases, the displacement across the isolator bearings becomes a larger portion of the first modal response.

University of Southern California University Hospital (USCUH)

The USCUH was also instrumented by CDMG in 1989. The records that have been utilized for this study are those from the preliminary release of the 1992 Landers [CSMIP, 1994c], and the 1994 Northridge [CSMIP, 1994d] earthquakes. Table 4 shows the identified equivalent linear periods and damping for the first five modes using MODE-ID.

Table 4 USCUH identified model periods and equivalent viscous damping values.

EARTHQUAKE		Transverse				Longitudinal				Torsional	
		Mode 1		Mode 2		Mode 1		Mode 2		Mode 1	
	Time Segment (sec)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)	per (sec)	damp (%)
1992 Landers	0 - 10	0.89	3.5	0.40	12.3	0.86	8.1	0.36	7.5	0.74	-1.5
	10 - 20	1.16	10.9	0.43	9.1	0.97	13.1	0.44	14.1	0.71	0.4
	20 - 30	1.19	8.1	0.51	7.1	1.13	12.0	0.48	9.8	1.09	3.6
	30 - 40	1.22	11.4	0.50	10.3	1.16	12.3	0.48	9.7	0.90	-6.0
	40 - 50	1.20	8.8	0.51	5.6	1.13	10.1	0.46	9.0	1.01	-9.2
	50 - 60	1.16	7.4	0.49	9.3	1.11	12.5	0.44	9.0	0.97	2.3
	60 - 70	1.10	10.7	0.44	10.2	1.05	12.8	0.41	9.6	0.80	2.1
	70 - 80	1.08	7.4	0.45	9.2	1.05	11.9	0.44	6.8	1.04	6.5
	80 - 90	1.00	10.7	0.42	8.0	0.96	13.0	0.41	9.8	1.03	-0.6
1994 Northridge	0 - 10	0.86	2.4	0.39	10.2	0.79	7.9	0.38	9.7	0.68	-3.3
	10 - 20	1.42	11.1	0.56	16.5	1.42	20.6	0.52	14.1	0.89	8.0
	20 - 30	1.30	12.6	0.53	13.6	1.36	12.4	0.52	5.0	1.28	5.2
	30 - 40	1.25	9.4	0.51	13.8	1.29	11.6	0.48	13.3	1.08	0.8
	40 - 50	1.24	10.7	0.53	8.6	1.14	10.8	0.48	9.4	1.14	3.5
	50 - 60	1.17	11.3	0.46	14.6	1.14	13.5	0.46	10.1	1.11	4.9
Fixed Base [Halling, 1995]		1.35				1.13				0.84	

The foundation excitation from the Landers and Northridge transverse (channel 7) and longitudinal (channel 5) directions are shown in figure 1. The 30-40 sec and 10-20 sec segments of the Landers and Northridge events, respectively, contain the most intense motions.

The identified modal periods indicate that the fixed-base periods of the models from Halling [1995] may be higher than the actual fixed-base period of the structure. The torsional mode exhibits artificial negative damping in several segments of the Landers and Northridge earthquakes. This is probably the result of translational excitation producing a torsional response. Due to the very non-regular shape of this building in both plan and elevation, some torsional response is expected.

Again, as noted with the FCLJC and the FCCF structures, the first transverse and longitudinal modal periods begin low, increase as the response builds up, and then decrease. The damping follows similar trends for the Northridge earthquake, and to a lesser degree for the Landers earthquake. Figure 2 shows the identified first transverse and longitudinal mode shapes from segments of the time histories. Again as the amplitude of response increases, the displacement across the isolator bearings becomes a larger portion of the first modal response.

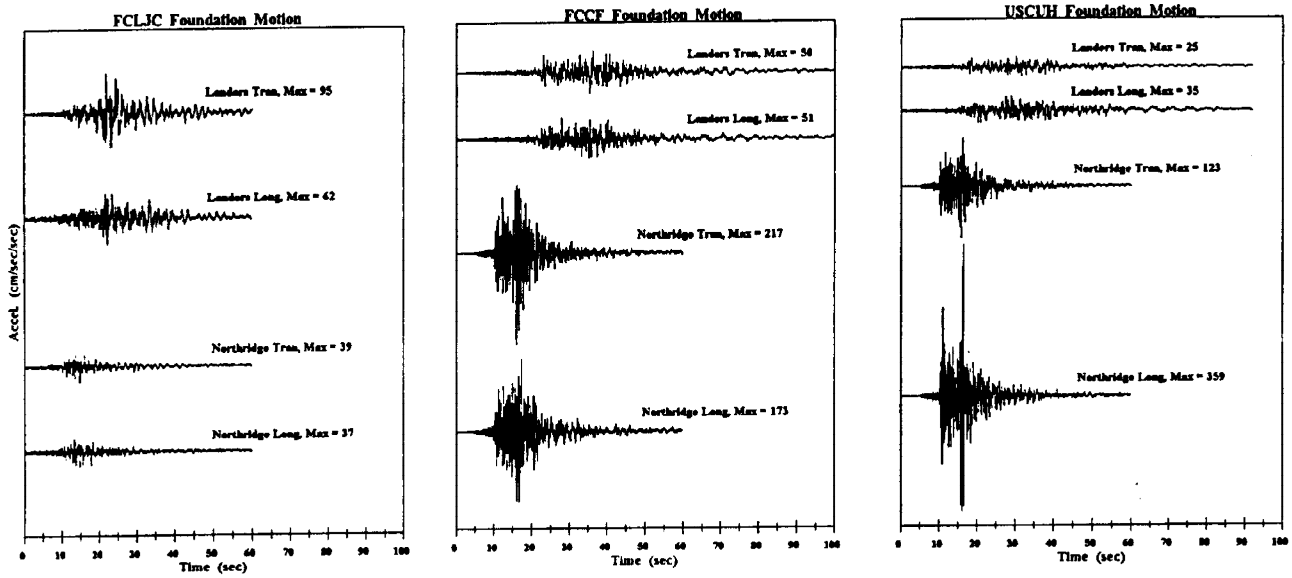

Figure 1 Landers earthquake and Northridge earthquake foundation acceleration histories for each building.

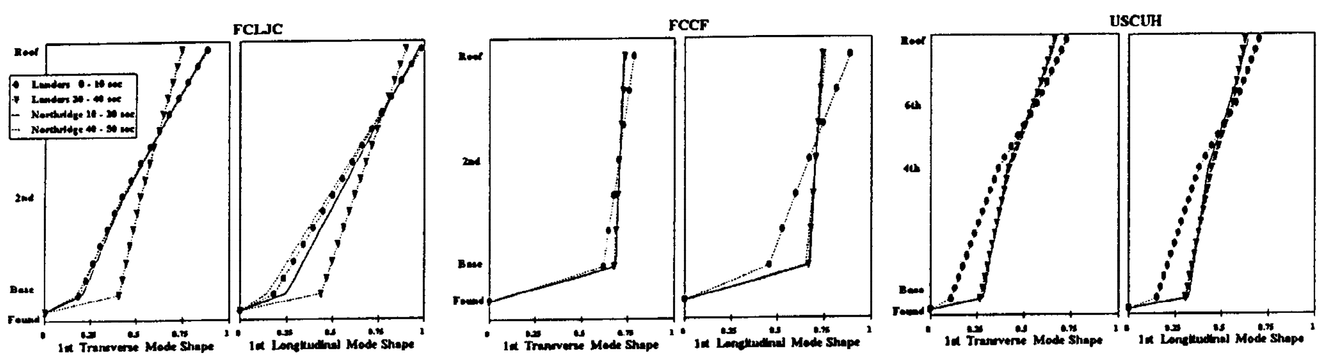

Figure 2 First transverse and first longitudinal mode shapes of each building for the 0 to 10 sec and 30 to 40 sec segments of Landers earthquake, and the 10 to 20 sec and 40 to 50 sec segments of Northridge earthquake.

CONCLUSIONS

This study shows in a systematic way the variation of structural properties from recent California earthquakes. In particular, as input excitation is increased, the equivalent linear period and viscous damping increase. Also the portion of the first mode displacement that takes place at the isolation level increases. In all earthquakes studied, including the 1994 Northridge, the equivalent linear period of response is well below that of the design period for each structure. This is consistent with the small bearing displacements that were determined from field observations following the earthquakes. Field observations indicated maximum bearing displacements of 2.5 to 3.5 cm at the FCCF and 2.5 to 4.0 cm at the USCUH.

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