

**PERFORMANCE UPDATE OF BASE ISOLATED BUILDINGS INSTRUMENTED BY CSMIP
IN LOS ANGELES IN RECENT EARTHQUAKES**

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Abstract

The performance of University of Southern California (USC) hospital and Los Angeles County Fire Command and Control (FCC) buildings during the 1994 Northridge earthquake are two important case studies of how base-isolation can prevent significant structural damage during seismic activity. Both structures have experienced several ground motions of lesser intensity in the subsequent years. Analysis of the structural response to the later ground motions offers valuable insights into the structural parameters and bearing characteristics. This paper presents a comparative study of the evolving dynamic properties of the USC hospital and the FCC buildings using system identification based on vibration records.

Introduction

Seismic resilience of critical infrastructure is a fundamental requirement in earthquake-prone regions such as Southern California. The 1994 Northridge earthquake provided an invaluable opportunity to assess the real-world performance of base-isolated buildings designed to protect both structural systems and occupants. Among the most significant case studies are the University of Southern California (USC) hospital and the Los Angeles County Fire Command and Control (FCC) building, both of which were equipped with seismic isolation systems and extensively instrumented by the California Strong Motion Instrumentation Program (CSMIP).

The USC hospital, located near the intersection of Highways 5 and 10, is a seven-story steel-braced frame building, supported on a hybrid base-isolation system consisting of lead-rubber and elastomeric bearings (Asher et al. 1990). During the Northridge earthquake, the hospital experienced a peak free-field acceleration of 0.49g, yet the roof acceleration was reduced to approximately 0.21g - nearly 50% of the ground level motion. The base isolation system yielded, dissipated energy, and successfully limited inter-story drifts to less than 30% of code-specified values, ensuring elastic behavior of the superstructure. A detailed response analysis of the USC hospital building to the Northridge earthquake was performed by Nagarajaiah et al. (1995, 1996, 2000) to identify the modal properties of the building using both parametric and non-parametric system identification methods. The authors also used 3D non-linear modelling techniques (Nagarajaiah 1991) to analytically verify the identified modal properties. Seismic isolation modelling of the USC hospital was carried out by Asher et al. (1995) using a different approach. Çelebi (1996) conducted a similar performance evaluation of the USC hospital building to conclude that the building attained up to 10% hysteretic damping due to efficient base-isolation and reduced drift ratios of the superstructure of the building during the Northridge earthquake.

The FCC building, located in the City Terrace area of East Los Angeles, is a two-story steel frame structure with high-damping rubber bearings. In contrast to the USC hospital building, the response of the FCC building to the Northridge earthquake presented a unique performance outcome. Although base isolation was effective in reducing seismic demand, the building experienced unintended impact against an adjacent concrete entry bridge in the initial 16 seconds of the ground motion. This contact introduced higher-mode responses, leading to localized amplification of accelerations up to 0.35g at certain roof locations (Nagarajaiah et al. 2001). The incident highlighted the vulnerability of isolated structures to pounding when adequate separation gaps are not maintained, despite otherwise satisfactory seismic performance after the pounding ceased. Nagarajaiah et al. (1995 1996, 2001) conducted system identification and analytical modelling of the FCC building to identify the modal properties of the building. However, the pounding behavior of the FCC building was unique to the 1994 Northridge earthquake, and the FCC's response to the later earthquakes post-1994 does not show any such effect.

After the major 1994 Northridge earthquake, both the USC hospital and the FCC buildings have undergone subsequent seismic events over the years. Although the later ground motions were significantly smaller compared to the Northridge earthquake, the response of the structures to these smaller seismic events can help to track the evolution of their dynamic characteristics. Such studies detect any change in the structural parameters like natural modal periods, damping ratios and behavior of isolators due to aging or any other structural modifications. These observations provide valuable insights into the long-term reliability of base-isolated structures and the need for continuous monitoring to ensure sustained performance.

This study focuses on the identification of the modal periods and damping ratios of the USC Hospital and FCC buildings during the Northridge earthquake and ground motions from the subsequent years. Two time-domain methods - the SSI-Cov (Covariance-based Stochastic Subspace Identification, Van Overschee et al. 2012), which is an output-only method, and the OKID/ERA (Observer Kalman filter Identification / Eigenvalue Realization Algorithm, Juang et al. 1993), which is an input-output method, are adopted to estimate the modal properties of the structures. A comparative analysis of the identified modal periods and damping ratios is presented for both USC Hospital and FCC buildings corresponding to seismic events in 1994 and subsequent years.

USC Hospital Building

The USC hospital is a base-isolated, seven-story, steel-braced framed building with seven stories above ground and a basement. It has 10 bays in the east-west (EW) direction and 12 bays in the north-south (NS) direction. The floor plan is asymmetric with two wings, connected by a necked down region of the base. The building has setbacks after the fifth floor. Metal decking and a grid of steel beams support all concrete floors in the building. The base-isolation system of the USC building consists of 68 lead-rubber bearings and 81 elastomeric bearings, as shown in Figure 1. More structural details on the USC hospital building can be found in (Asher et al. 1990, Nagarajaiah et al. 2000).

The building is extensively instrumented by the CSMIP with sensors at different locations, as shown in Figure 1. The accelerometers [referred to as channels (CHNs)] are centrally located at the foundation (CHN5 and CHN7), lower level or base (CHN9 and CHN11), fourth floor (CHN13

and CHN15), sixth floor (CHN17 and CHN19), and roof (CHN21 and CHN23) in the NS and EW directions, respectively. Sensors (CHN6/8, CHN10/12, CHN14/16, CHN18/20, and CHN22/24) are located at the east and west ends of the corresponding floors to measure lateral-torsional motions, respectively. Three sensors (CHN25, CHN26, and CHN27) are embedded in the ground to record the free-field ground motion. Sensors CHN1/3 and CHN2/4 measure the vertical response at the foundation level and lower or base level, respectively.

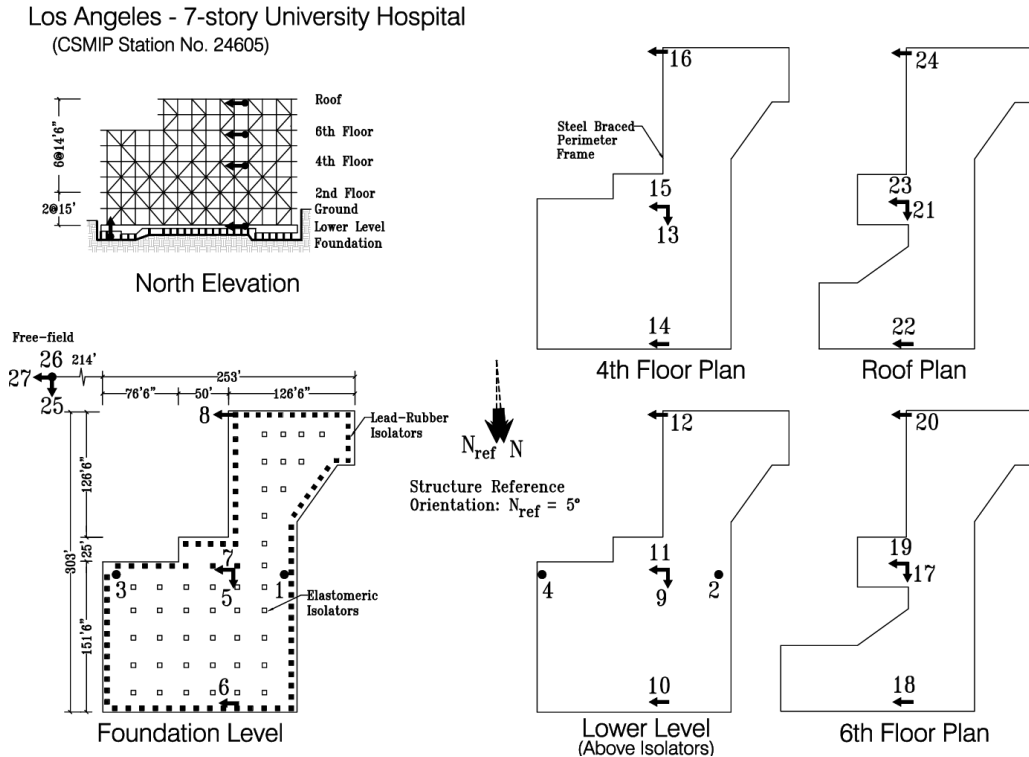


Figure 1: USC hospital building plan and sensor locations

In the analysis presented here, only lateral vibration modes have been considered in east-west (EW) and north-south (NS) directions independently. For identification of the modal properties of the building with base-isolation (BI), the ground acceleration at the foundation level can be considered as input, and the data from the lower level, 4th, 6th, and the roof as output. The approximate fixed-base (FB) modes of the building (without base-isolation) can be estimated by considering the acceleration at the lower (base) level as input and data from the 4th, 6th, and roof as output. The different channels used for system identification are shown in Table 1.

Table 1: USC hospital sensors used for base-isolated and fixed-base analysis

North-South Direction				East-West Direction			
NS-BI		NS-FB		EW-BI		EW-FB	
Input	Output	Input	Output	Input	Output	Input	Output
CHN 5	CHN 9	CHN 9	CHN 13	CHN 7	CHN 11	CHN 11	CHN 15
	CHN 13		CHN 17		CHN 15		CHN 19
	CHN 17		CHN 21		CHN 19		CHN 23
	CHN 21		-		CHN 23		-

The datasets corresponding to different earthquakes recorded by CSMIP for the USC hospital building available on the CESMD (CSMIP 2025) website have been summarized in Table 2. In some of the earthquake records at USC hospital station, the data from the input channels are missing (denoted by the symbol ✖).

Table 2: Available sensor data for ground motions from 1994
✖ - missing, ✓ - available for processing

	PGA (g)	North-South Channels				East-West Channels			
		5	13	17	21	7	15	19	23
Northridge (1994)	0.490	✓	✓	✓	✓	✓	✓	✓	✓
Hector Mine (1999)	0.026	✖	✖	✖	✖	✖	✖	✖	✖
Beverly Hills (2001)	0.027	✖	✖	✖	✖	✖	✖	✖	✖
Whittier Narrows (2010)	0.019	✖	✓	✓	✓	✓	✓	✓	✓
Calexico (2010)	0.010	✖	✓	✓	✓	✓	✓	✓	✓
Borrego Springs (2010)	0.007	✓	✓	✓	✓	✓	✓	✓	✓
Encino (2014)	0.014	✖	✓	✓	✓	✖	✓	✓	✓
La Habra (2014)	0.011	✖	✓	✓	✓	✖	✓	✓	✓
Highland Park (2024)	0.096	✓	✓	✓	✓	✓	✓	✓	✓

Estimation of Base-Isolated Modal Properties

The analysis of the USC hospital dataset corresponding to the Northridge (1994) earthquake is shown in comparison to earlier estimates from 1995 (Nagarajaiah et al. 1995). The SSI-Cov method is applied to the output (only) data to estimate the frequencies and damping ratios corresponding to the base-isolated structure. SSI-Cov constructs the Hankel matrices based on output correlation, and then the stability chart can be used to select the stable modes. The modal periods and the damping ratios corresponding to the stable modes can then be estimated. The stability chart from the output data in the north-south direction for the base-isolated building is shown in Figure 2. Three stable modes corresponding to model order six are selected as the stable modes, and the periods (frequencies) and damping ratios corresponding to the first three modes are estimated as shown in Figure 2.

Since the input data (ground acceleration) and output data are available in the case of the Northridge earthquake (1994), the OKID/ERA method can be used to verify the base-isolated modes identified by SSI-Cov. First, the input-output data is used to estimate the Markov parameters, which were then used to construct the Hankel matrices. Then, the state space matrices are calculated and the modal properties like frequency and damping are obtained. The state space matrices can be further used to reconstruct the system output. The reconstructed or estimated

accelerations have been compared with the output data in Figure 3 to demonstrate how satisfactorily this method estimates the response.

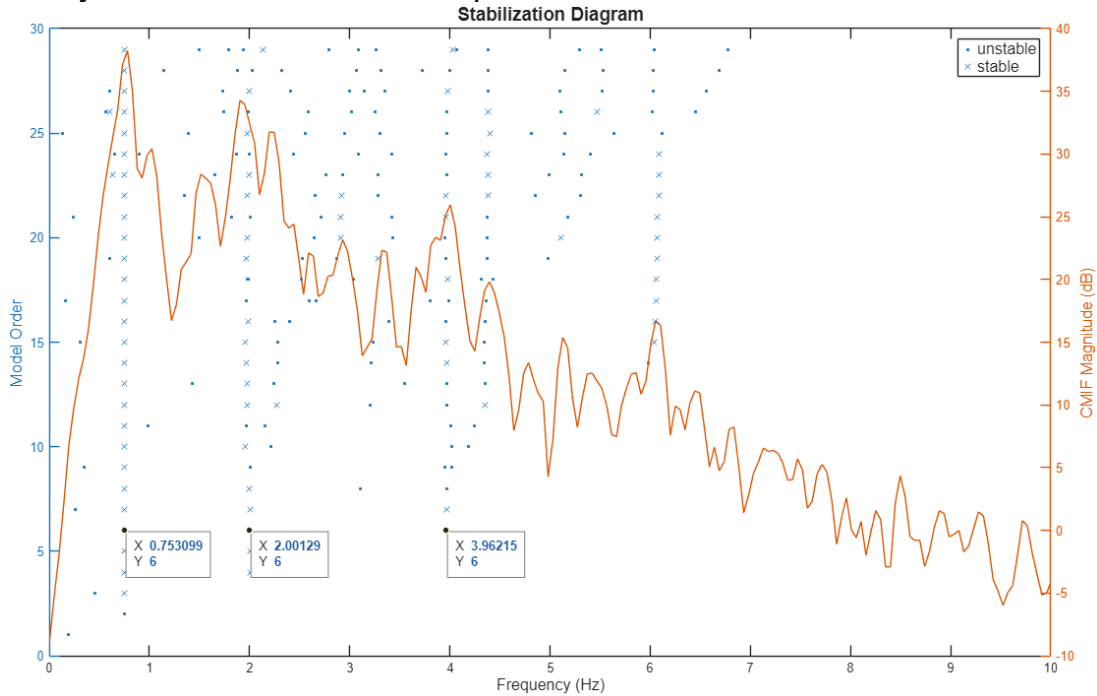


Figure 2: Stabilization chart in NS direction for base-isolated USC hospital building

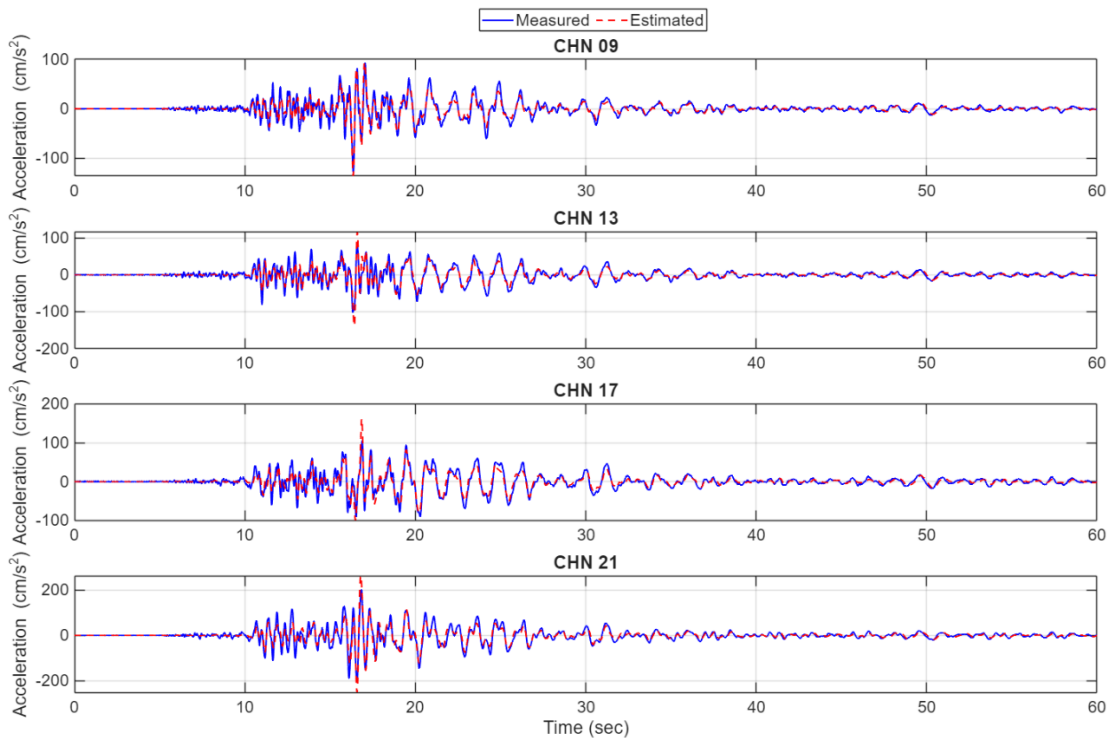


Figure 3: Measured vs estimated acceleration for base-isolated case using OKID/ERA in NS direction

The time periods and the damping ratios estimated by SSI-Cov and OKID/ERA are found to agree well with each other (not shown). The estimated parameters have been compared with those identified by Nagarajaiah et al. (2000) using frequency domain methods in Table 3.

Table 3: Identified time periods and damping ratios for base-isolated USC hospital building

North-South Direction				East-West Direction			
Estimated		Identified by Nagarajaiah et al. (2000)		Estimated		Identified by Nagarajaiah et al. (2000)	
T (sec)	ζ (%)	T (sec)	ζ (%)	T (sec)	ζ (%)	T (sec)	ζ (%)
1.33	14.7	1.38	13.0	1.27	9.4	1.32	15.0
0.52	10.6	0.53	14.0	0.56	9.2	0.51	17.0
0.25	4.2	0.25	5.0	0.29	6.4	0.27	7.0

The estimated periods and the damping ratios corresponding to the first three base-isolated modes of the USC hospital building are shown in Tables 4, 5, and 6. In some cases, the damping ratios could not be estimated reliably and hence they have not been reported in the tables. Among all the earthquakes, the Northridge (1994) earthquake had the strongest intensity, leading to yielding in the bearings. The other ground motions from the later years are of lower intensity, and as a result, the base-isolators do not yield and operate in the pre-yield range. Therefore, both the NS and EW time periods, corresponding to the first two modes for the Northridge earthquake, are significantly higher than the estimated time periods from the other earthquakes. Also, estimated damping for the first two modes is higher for the Northridge earthquake compared to the other ground motions, indicating significant energy dissipation due to hysteresis of the isolators.

Table 4: Estimated time periods and damping ratios for first base-isolated mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	1.33	14.7	1.27	9.4
Whittier Narrows	0.74	8.6	0.81	11.4
Calexico	0.75	-	0.89	8.2
Borrego Springs	0.77	9.4	0.85	8.6
Encino	0.75	11.4	0.84	-
La Habra	0.90	9.0	0.99	7.2
Highland Park	0.81	7.1	0.90	8.0

Table 5: Estimated time periods and damping ratios for second base-isolated mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.52	10.5	0.56	9.2
Whittier Narrows	0.37	6.0	0.36	8.6
Calexico	0.43	8.1	0.43	8.9
Borrego Springs	0.37	7.3	0.48	10.9
Encino	0.40	10.1	0.38	8.3
La Habra	0.44	8.2	0.46	-
Highland Park	0.40	8.3	0.51	11.3

Table 6: Estimated time periods and damping ratios for third base-isolated mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.25	4.2	0.29	6.4
Whittier Narrows	0.23	5.4	0.26	4.6
Calexico	0.26	6.5	0.26	4.0
Borrego Springs	0.27	4.9	0.26	-
Encino	0.25	6.6	0.30	-
La Habra	0.28	6.2	0.27	-
Highland Park	0.24	5.3	0.29	6.4

The estimated time periods for the base-isolated structure have been compared in Figure 4 for different earthquakes across the years. It may be observed here that the time periods in both NS and EW directions are much higher for the Northridge (1994) earthquake compared to subsequent earthquakes, showing full activation of the base-isolation bearings past yield. The first two periods for earthquakes other than the Northridge are quite close to each other. The third base-isolated time period remains consistent across all the earthquakes. Further, the damping ratios for the first three base-isolated modes are shown in Tables 4, 5, and 6. The damping ratios corresponding to the first two modes for each earthquake are higher due to base isolation, and the third mode damping is lower compared to the first two modes, which is expected in base-isolated structures.

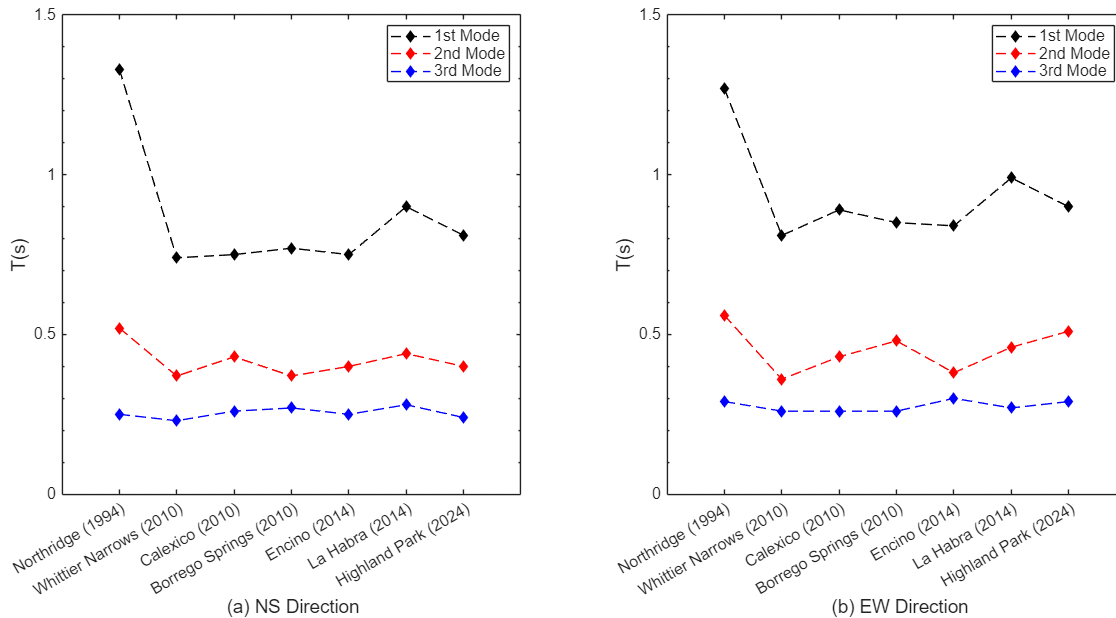


Figure 4: Time-periods estimated across different earthquakes for base-isolated USC hospital

The first two base-isolated mode shapes for Borrego Springs and Northridge earthquakes are compared in Figure 5 for NS (a-b) and EW (c-d) directions. The first mode shape for the Northridge earthquake is dominated by the base isolation flexibility, and therefore, shows a larger drift at the first floor (lower level) compared to the Borrego Springs earthquake.

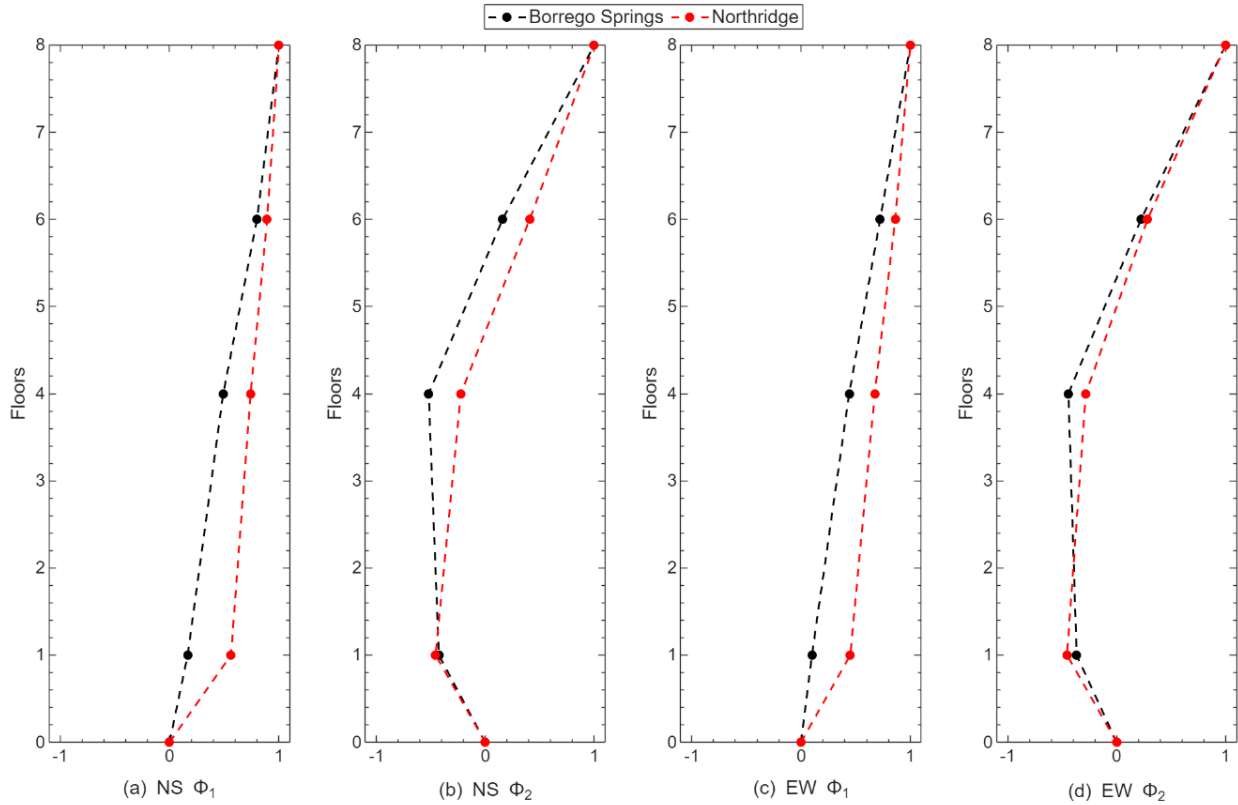


Figure 5: First two base-isolated mode shapes for Northridge and Borrego Springs earthquakes

The statistical distribution (violin plot) of the estimated time periods for the ground motions after 1994 have been compared to the time periods estimated from the Northridge data in Figure 6. The difference in the first mode time period between Northridge and other earthquakes is the largest, while the third mode time period remains the same for all the earthquakes.

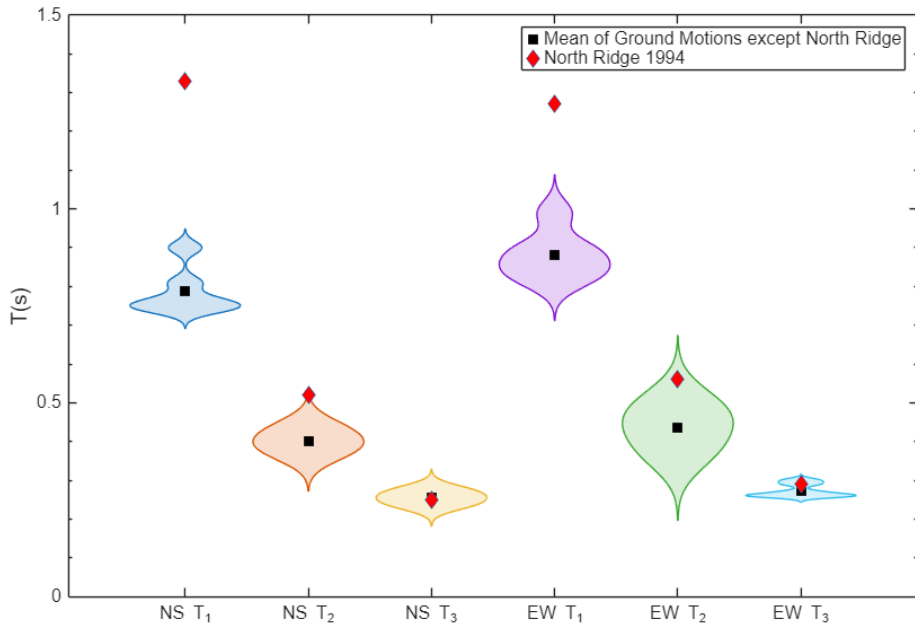


Figure 6: Comparison of base-isolated mode periods from Northridge data with subsequent earthquakes

Estimation of Approximate Fixed-Base Modal Properties

The approximate fixed-based modal periods and damping ratios are estimated using the OKID/ERA method with the acceleration at the lower level (above base-isolators) as input. It is based on the assumption that the superstructure is excited by the acceleration at the lower level, neglecting the filtering that occurs through the flexible base isolation system pre-yield. Hence, the estimated fixed-base modes are not expected to be very accurate but provide an approximate idea about the superstructure flexibility alone (without the bearings). OKID is used to identify the Markov parameters based on the input-output data, followed by estimation of the modal properties and state space matrices by ERA. The reconstructed response for the fixed-base structure has been compared with the sensor output data in Figure 7 for Northridge, which is found to be satisfactory.

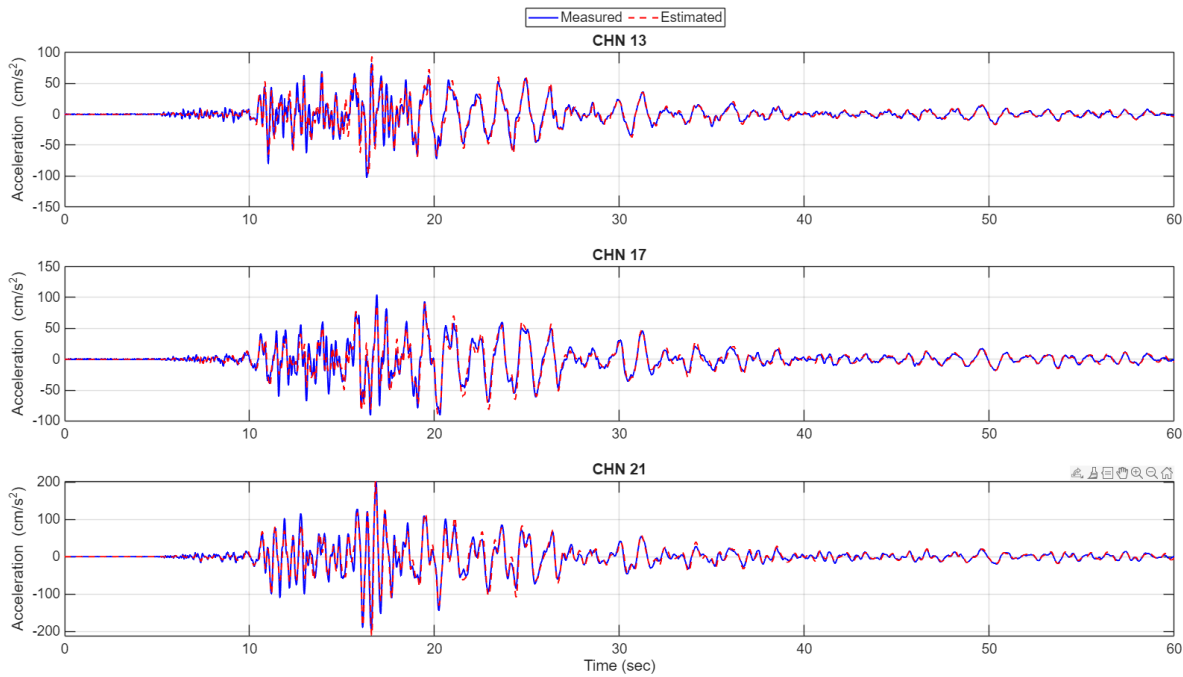


Figure 7: Measured vs estimated acceleration for fixed-base case using OKID/ERA in NS direction

The approximate fixed-base mode periods and damping ratios identified from the Northridge (1994) earthquake data using time domain methods in this study have been compared with those identified in Nagarajaiah et al. (2000) using frequency domain methods in Table 7; the results are found to be satisfactory.

Table 7: Identified time periods and damping ratios for fixed-base USC hospital building

North-South Direction				East-West Direction			
Estimated		Identified by Nagarajaiah et al. (2000)		Estimated		Identified by Nagarajaiah et al. (2000)	
T (sec)	ζ (%)	T (sec)	ζ (%)	T (sec)	ζ (%)	T (sec)	ζ (%)
0.76	5.4	0.76	3.0	0.85	6.0	0.92	2.0
0.32	8.0	0.34	3.0	0.35	4.0	0.37	2.0
0.18	7.9	0.22	5.0	0.17	5.4	0.20	4.0

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Similarly, the approximate fixed-base periods and damping ratios for the USC hospital building for all the ground motions are estimated using OKID/ERA with the acceleration at the base level (above the isolation system) as the input. The identified modes for the first three modes are presented in Tables 8, 9, and 10.

Table 8: Estimated time periods and damping ratios for first fixed-base mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.76	5.4	0.85	6.0
Whittier Narrows	0.68	4.7	0.71	6.3
Calexico	0.70	4.1	0.79	4.2
Borrego Springs	0.69	4.2	0.79	4.6
Encino	0.68	4.6	0.79	5.2
La Habra	0.71	5.4	0.82	3.3
Highland Park	0.70	5.7	0.82	3.3

Table 9: Estimated time periods and damping ratios for second fixed-base mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.32	8.0	0.35	4.0
Whittier Narrows	0.29	7.2	0.32	7.0
Calexico	0.30	6.7	0.35	4.9
Borrego Springs	0.29	7.2	0.34	6.7
Encino	0.29	7.8	0.35	6.3
La Habra	0.31	8.5	0.33	6.6
Highland Park	0.30	7.2	0.33	6.9

Table 10: Estimated time periods and damping ratios for third fixed-base mode

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.18	7.9	0.17	5.4
Whittier Narrows	0.17	7.1	0.18	4.0
Calexico	0.18	8.3	0.18	6.6
Borrego Springs	0.17	7.1	0.18	5.4
Encino	0.16	5.8	0.14	4.3
La Habra	0.18	8.5	0.19	6.4
Highland Park	0.16	7.4	0.16	4.2

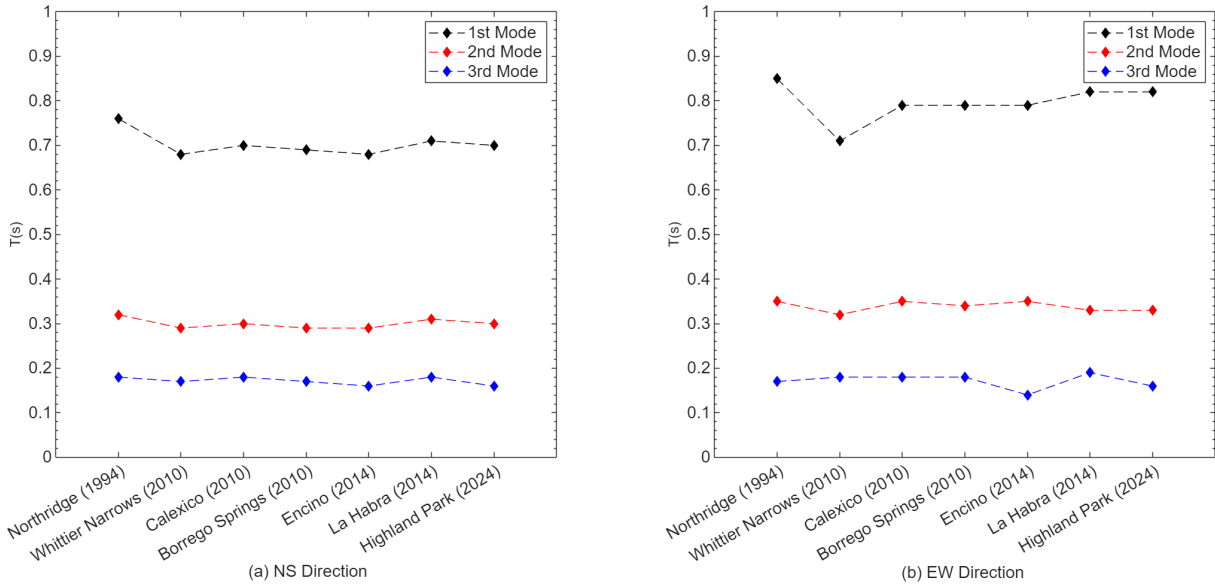


Figure 8: Time-periods estimated across different earthquakes for fixed-base modes of USC hospital

The variation of the estimated fixed-base mode periods across different earthquakes is shown in Figure 8. The estimated first modal periods indicate minor changes resulting from slight variations in superstructural stiffness, while the other two modal periods do not vary as much. The damping ratios vary in the range of 4 to 8%. Approximate first and second fixed base mode shapes are shown in Figure 9.

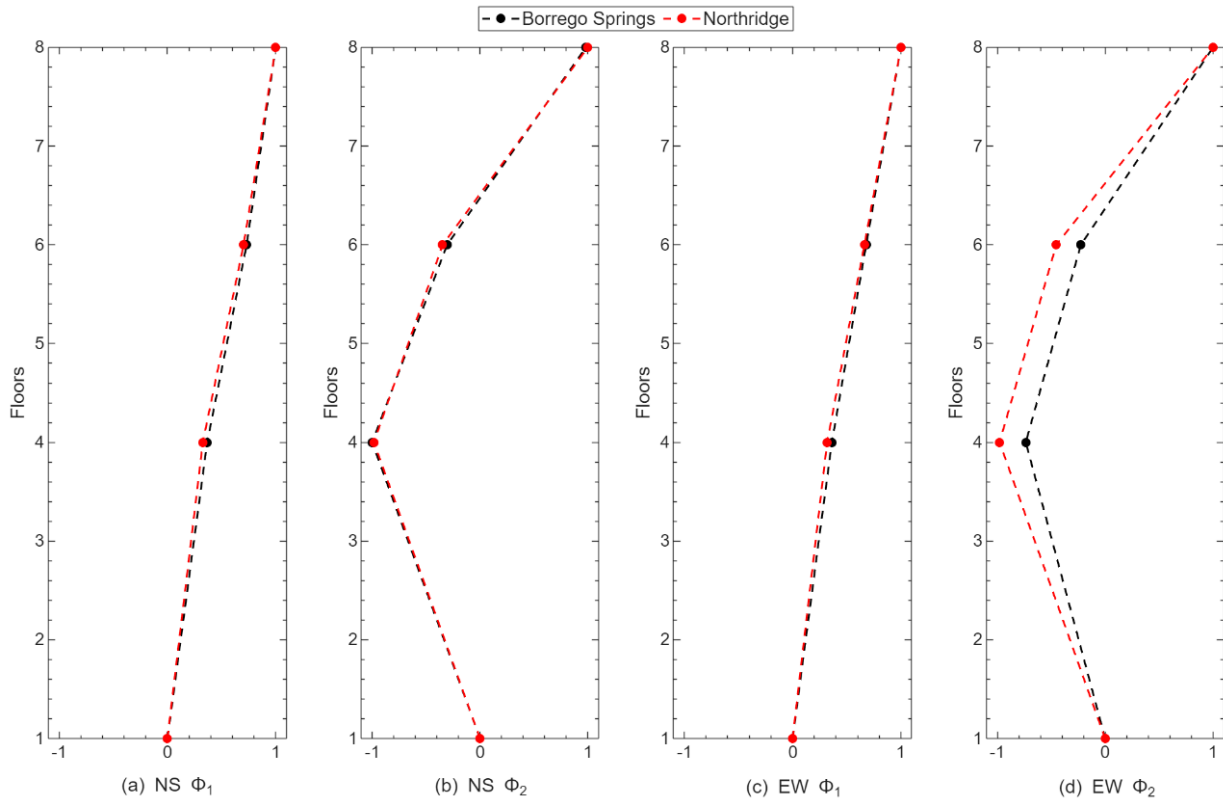


Figure 9: Approximate first two fixed-base modes in Northridge and Borrego Springs earthquakes

The statistical distribution (violin plot) of the fixed base time periods from the earthquakes during and after 1994 have been compared with the Northridge earthquake in Figure 10. The first mode fixed base period is slightly higher for the Northridge (1994) earthquake compared to the later years, indicating minor changes in superstructure stiffness. However, no significant changes are observed in the second and third mode periods across all earthquakes.

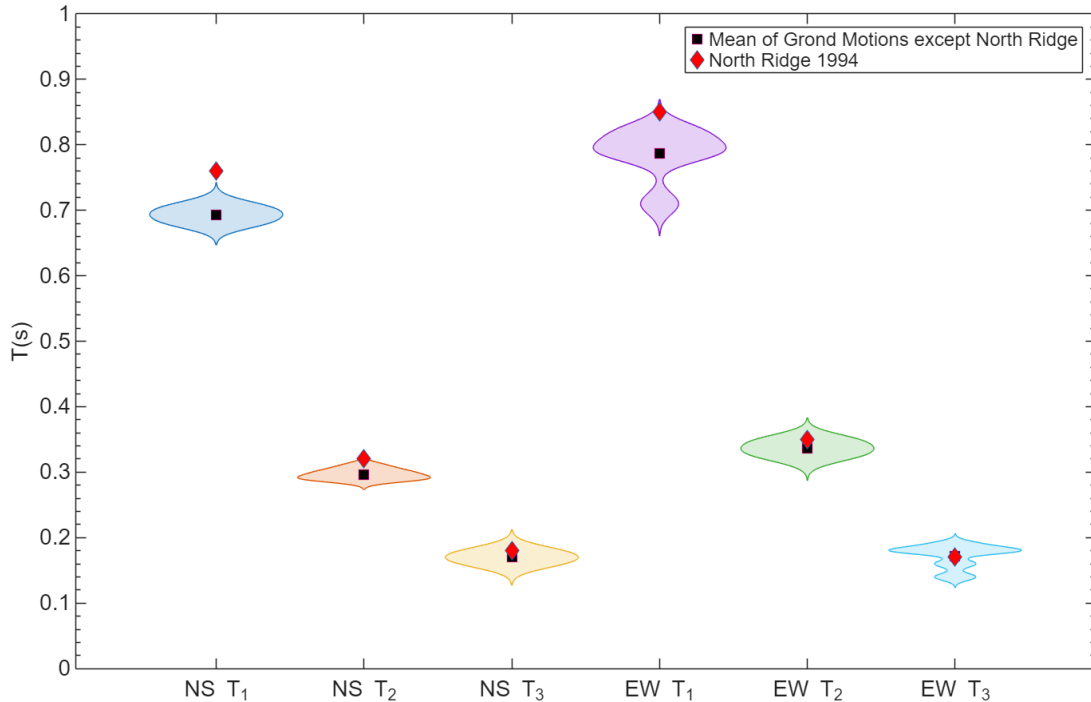


Figure 10: Comparison of the USC fixed-base periods from Northridge data with subsequent earthquakes

FCC Building

The FCC building is a base-isolated two-story building with seven bays in the north-south (NS) direction and three bays in the east-west (EW) direction (as shown in Figure 10). The steel-braced frame superstructure is supported by 32 high damping rubber bearings. The base, first floor, and the roof are made of concrete slabs on metal decking, supported on a grid of steel beams. The rubber bearings are in square shape of 16-inch length and 14.2-inch height. More design details about the building structure and base isolation systems are available in (Nagarajaiah et al. 2001).

The FCC building is instrumented with accelerometers by CSMIP (as shown in Figure 11). The accelerometers CHN 5-7, installed at the foundation level, record the ground motion used as input for the modal identification of the base-isolated building. At the base level (1st floor), CHN 9-11 record the acceleration in the EW direction while CHN 8 records the NS acceleration. Similarly, CHN 12 at the 2nd floor and CHN 14-16 at the roof record the EW acceleration, while CHN 13 records the NS roof acceleration. For the identification of the approximate fixed-base modes, the recorded acceleration at the base level (1st floor) is considered as input. The channels used for the identification of base-isolated and fixed-base modes in NS and EW directions are shown in Table 11.

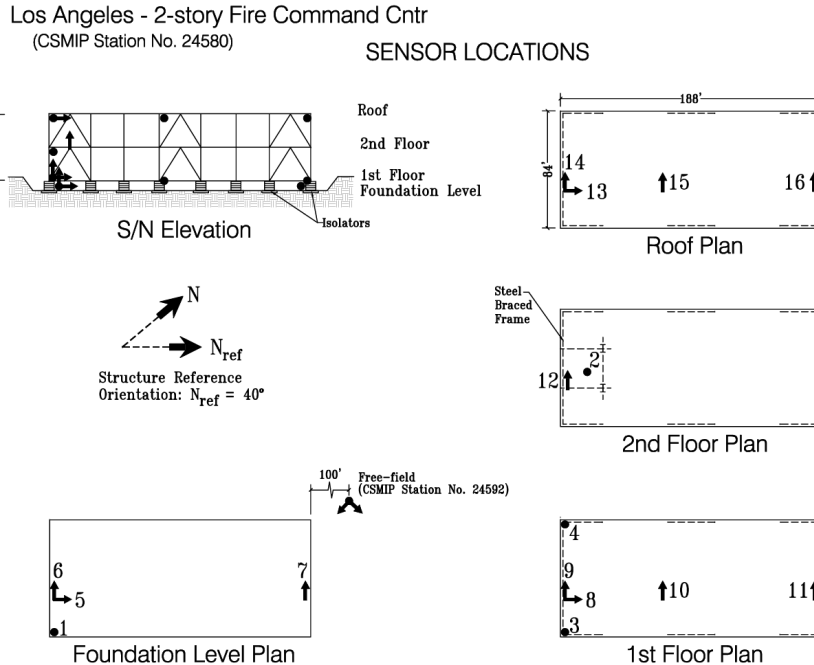


Figure 11: FCC building elevation, plan and sensor locations

Table 11: FCC building sensors used for base-isolated (BI) and fixed-base (FB) analysis

North-South Direction				East-West Direction			
NS-BI		NS-FB		EW-BI		EW-FB	
Input	Output	Input	Output	Input	Output	Input	Output
CHN 5	CHN 8	CHN 8	CHN 13	CHN 6	CHN 10	CHN 10	CHN 15
	CHN 13				CHN 15		

In the case of the FCC building under the 1994 Northridge earthquake, the response in the east-west direction was heavily corrupted by one-sided impact against the concrete entry bridge in the north-east corner of the building (as shown in Figure 12) up to 16 seconds. The acceleration time history recorded by CHN 9 -11 (Figure 13 a-c) on the first floor and by CHN 14-16 (Figure 13 d-f) at the roof level demonstrates a sharp increase in higher mode response in each upper half-cycle, between 12-16 sec. Pounding increased the peak acceleration from 0.22g at the foundation level to 0.32g at the roof level. Therefore, the Northridge earthquake data, after 16 seconds, is used in this study for the identification of the modes. For the other ground motions after 1994, this pounding effect was not observed and hence the full datasets are used for the analysis.

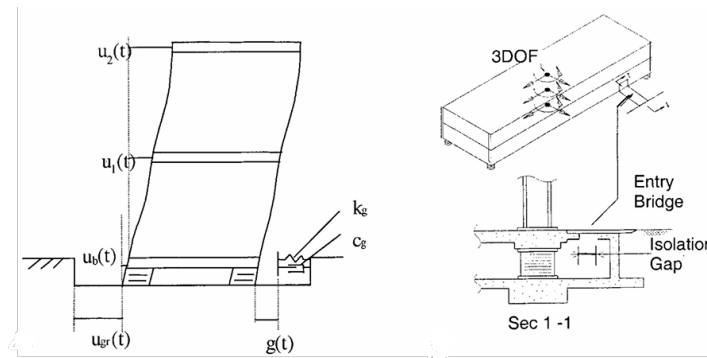


Figure 12: Analytical model, entry bridge and isolation gap in FCC building (Nagarajaiah et al. 2001)

Starting from the Northridge earthquake (1994), a total of nine ground motions were recorded at the FCC station (as shown in Table 12). All nine datasets (CSMIP 2025) corresponding to each ground motion were analyzed to estimate the modal properties of the FCC building over the years.

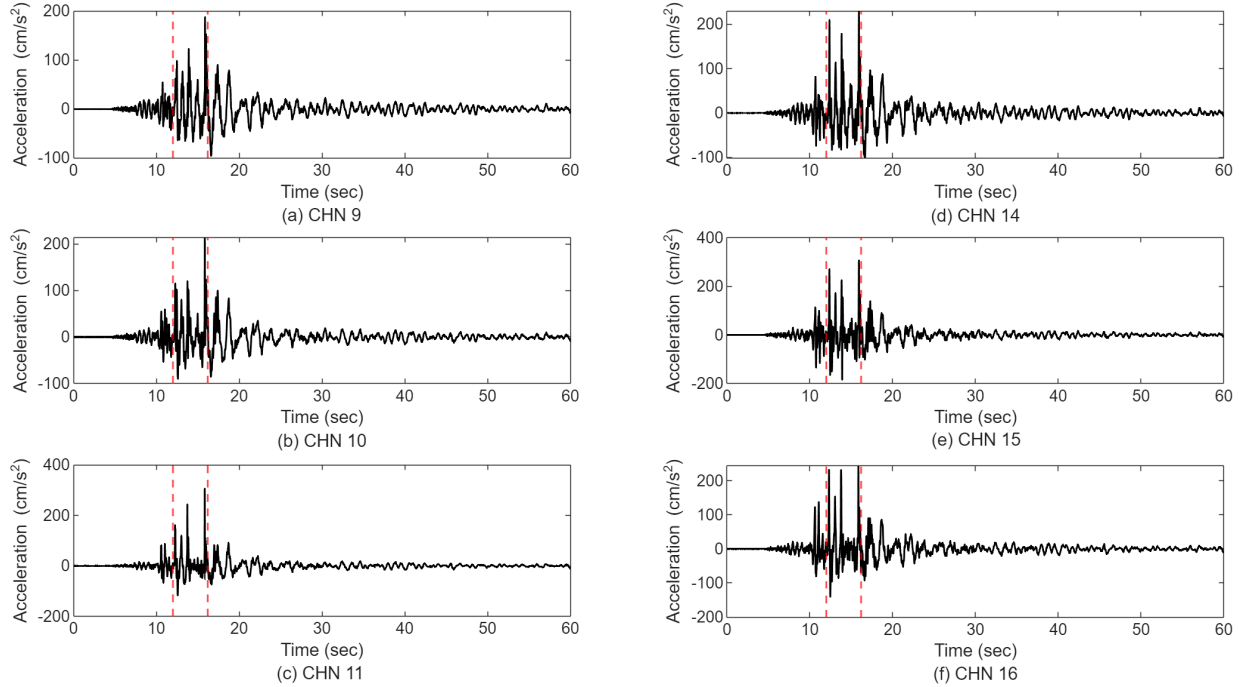


Figure 13: Time history in CHN 9-11 (a-c) and in CHN 14-16 (d-f) showing pounding between 12-16 sec

Table 12: Available sensor data for ground motions from 1994 for FCC building

	PGA (g)	NS Channels			EW Channels									
		5	8	13	6	7	9	10	11	12	14	15	16	
Northridge (1994)	0.220	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Encino (2014)	0.022	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
La Habra (2014)	0.033	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Rowland Heights (2014)	0.010	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ridgecrest (2019)	0.013	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Ridgecrest (5th Jul 2019)	0.019	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
South El Monte (2020)	0.065	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Lamont (2024)	0.006	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Highland Park (2024)	0.078	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Estimation of Base-Isolated Modal Properties

The vibration data of the FCC building is analyzed, assuming the lateral vibration modes in the NS and EW directions are independent due to the symmetry of the building (not considering the period during which pounding is observed). The estimated modal periods and the damping ratios have been shown in Tables 13, 14, and 15. It may be noted here that the 1994 Northridge earthquake was of much larger intensity compared to the remainder of the ground motions from later years. As a result, in the case of the Northridge earthquake, the base isolators were fully activated, and the first mode period was significantly higher compared to others. The base-isolated modal periods and damping ratios for the Northridge earthquake (1994) identified by Nagarajaiah et al. (2001) using the frequency domain method (available only in the EW direction), are also provided in Tables 13, 14, and 15 for comparison.

Table 13: Estimated time periods and damping ratios for first base-isolated mode
(* identified in Nagarajaiah et al. 2001)

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	1.31	-	1.52 (1.34*)	10.1 (11.0*)
Encino	0.53	8.8	0.55	9.6
La Habra	0.70	9.4	0.78	8.9
Rowland Heights	0.62	9.6	0.56	8.4
Ridge Crest (4th Jul)	0.68	5.9	0.66	10.1
Ridge Crest (5th Jul)	0.63	10.9	0.61	11.0
South El Monte	0.50	13.1	0.57	8.8
Lamont	0.55	4.2	0.64	5.6
Highland Park	0.53	5.8	0.54	12.1

Table 14: Estimated time periods and damping ratios for second base-isolated mode
(* identified in Nagarajaiah et al. 2001)

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.19	5.7	0.21 (0.18*)	8.7 (10.0*)
Encino	-	-	0.21	6.0
La Habra	0.18	4.5	0.21	4.3
Rowland Heights	0.16	11.8	0.15	8.4
Ridge Crest (4th Jul)	0.16	11.1	0.19	9.8
Ridge Crest (5th Jul)	0.17	10.5	0.17	-
South El Monte	0.16	6.1	0.20	4.1
Lamont	0.17	5.7	0.23	10.1
Highland Park	0.15	9.2	0.17	4.9

Table 15: Estimated time periods and damping ratios for third base-isolated mode (* identified in Nagarajaiah et al. 2001)

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.10	1.9	0.12 (0.11*)	4.1(5.0*)
Encino	0.13	3.3	0.10	1.0
La Habra	0.13	1.3	0.12	2.4
Rowland Heights	0.10	2.4	0.11	3.6
Ridge Crest (4th Jul)	0.13	0.9	0.13	2.9
Ridge Crest (5th Jul)	0.13	3.8	0.11	2.7
South El Monte	0.12	1.9	0.12	4.9
Lamont	0.11	1.7	0.12	1.1
Highland Park	0.10	5.0	0.11	2.6

The variation of the estimated time periods across different earthquakes is shown in Figure 14. It can be observed that the first period is significantly higher for the Northridge earthquake due to the full activation of the base-isolators, while the second and third mode periods remain almost the same across the different ground motions.

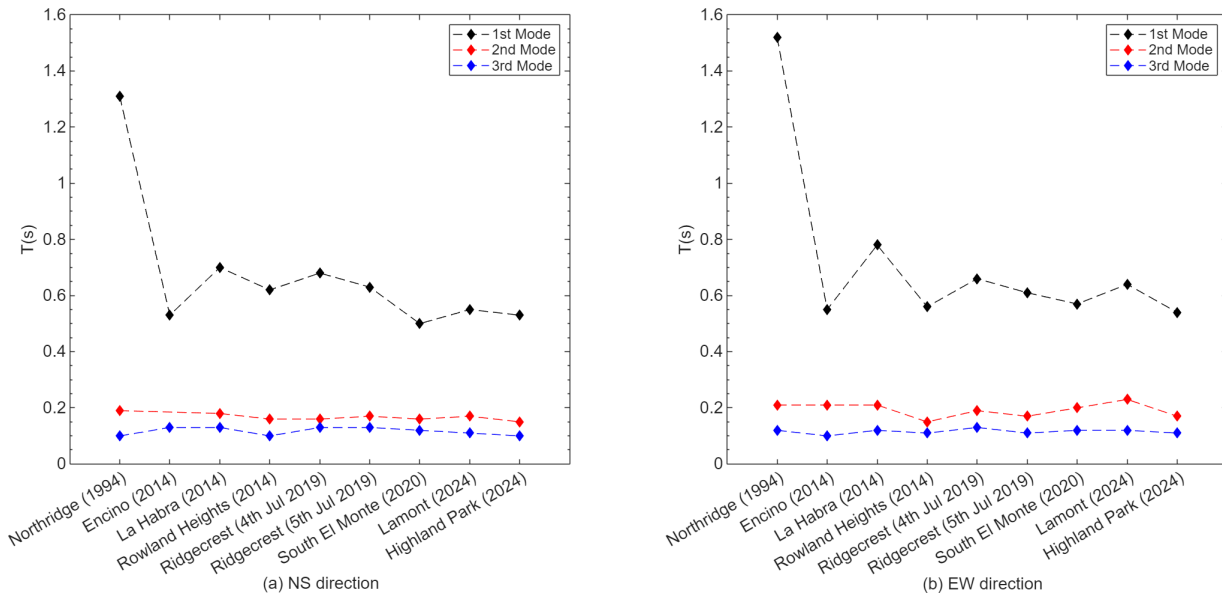


Figure 14: Time-periods estimated across different earthquakes for base-isolated modes of FCC building

The estimated damping ratios for the first three modes across different ground motions, as shown in Tables 13, 14, and 15, display a wide variation and may therefore not be very accurate. The first two base-isolated mode shapes are shown in Figure 15 for NS and EW directions. It may be observed that in the first mode shape, the displacement of the first floor is larger in the case of Northridge compared to the Lamont earthquake due to activation of base-isolation flexibility, while the second mode shape remains the same for both earthquakes.

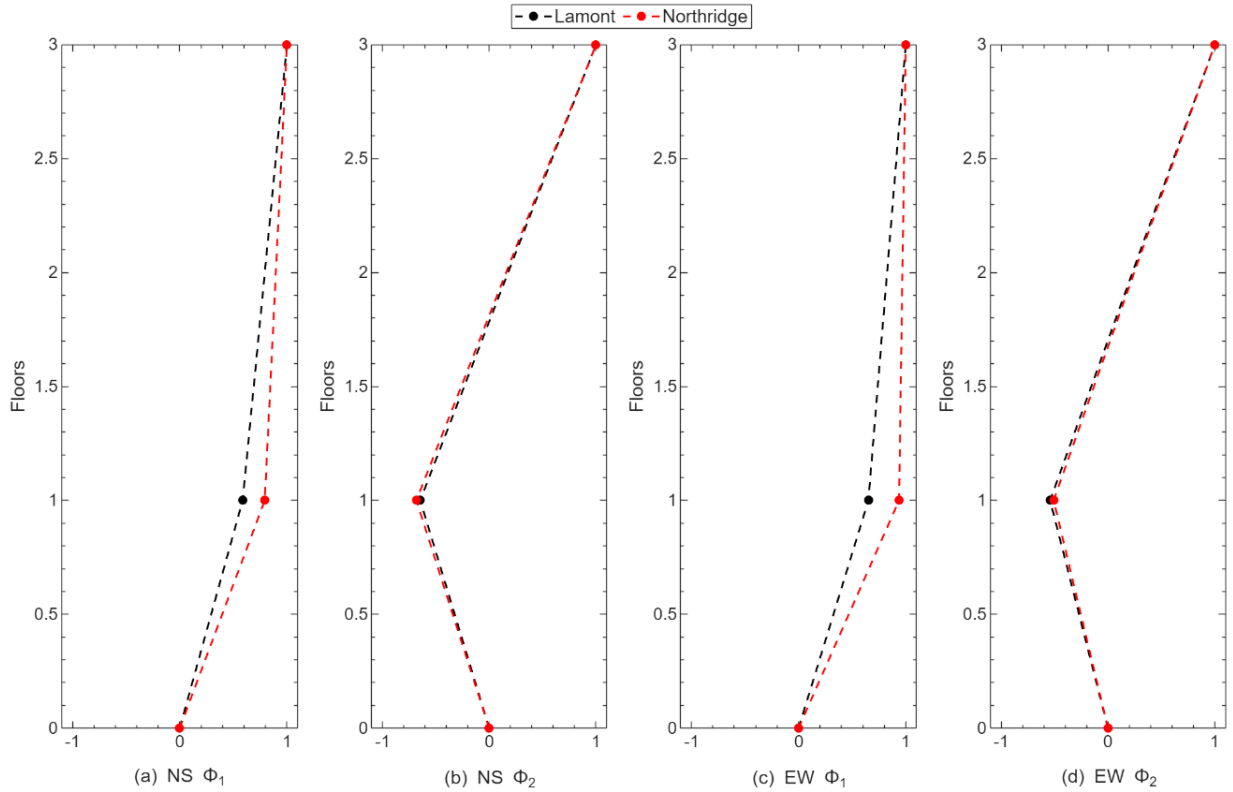


Figure 15 First two base-isolated mode shapes of FCC building in Lamont and Northridge earthquakes

The statistical distribution (violin plot) of the modal periods estimated from ground motions during and after 1994 have been compared to the Northridge earthquake in Figure 16. A significant difference between the first modal period of Northridge and the other earthquakes is observed, while the second and third modes of variation are not as significant for all earthquakes.

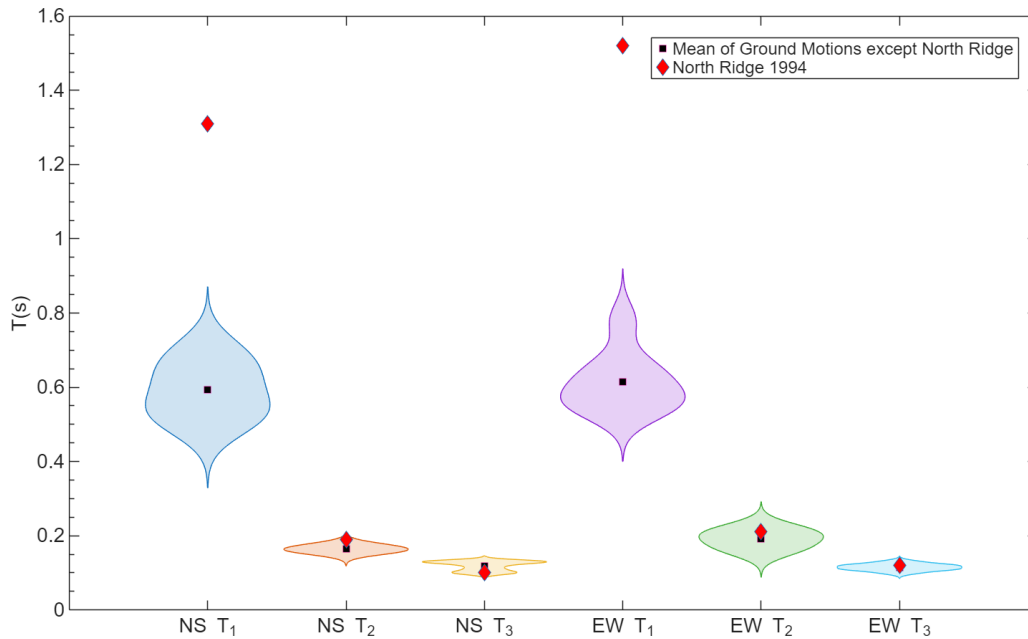


Figure 16: Comparison of base-isolated modal periods from Northridge data with subsequent earthquakes

Estimation of Approximate Fixed-Based Modal Properties

The approximate fixed-base modes are estimated using the acceleration at the first floor (above base-isolators) as input. Since the building is two-storied above the base, we can have two modes in each of the NS and EW directions. The estimated modal periods and the damping ratios have been tabulated below in Tables 16 and 17. The EW fixed-base time periods estimated from the Northridge (1994) data have also been compared with those identified using the frequency domain method by Nagarajaiah et al. (2001).

Table 16: Estimated time periods and damping ratios for first fixed-base mode
(* identified in Nagarajaiah et al. 2001)

	North South		East West	
	T (sec)	ζ (%)	T (sec)	ζ (%)
Northridge	0.30	7.4	0.34 (0.35*)	5.3
Encino	0.32	9.6	0.27	9.7
La Habra	0.26	4.6	0.31	7.4
Rowland Heights	0.31	9.8	0.31	2.3
Ridge Crest (4th Jul)	0.31	2.7	0.30	2.9
Ridge Crest (5th Jul)	0.33	6.4	0.30	1.2
South El Monte	0.27	9.1	0.31	7.2
Lamont	0.33	10.3	0.31	6.2
Highland Park	0.24	4.6	0.28	3.2

Table 17: Estimated time periods and damping ratios for second fixed-base mode
(* identified in Nagarajaiah et al. 2001)

	North South		East West	
	T (sec)	Damping (%)	T (sec)	Damping (%)
Northridge	0.12	2.4	0.13 (0.11*)	2.6
Encino	0.14	4.8	0.11	5.8
La Habra	0.13	1.3	0.13	2.4
Rowland Heights	0.12	3.6	0.13	2.2
Ridge Crest (4th Jul)	0.13	2.7	0.13	2.2
Ridge Crest (5th Jul)	0.12	6.0	0.14	6.8
South El Monte	0.12	1.8	0.13	2.8
Lamont	0.13	4.0	0.12	1.1
Highland Park	0.12	1.1	0.13	5.0

A slight decrease in the mean first mode period is observed in the EW direction in the case of earthquake responses after 1994, in comparison to the Northridge 1994 earthquake response. The modal periods and damping ratios remain similar across the years, showing there is no significant change in the superstructure over the years.

The statistical distribution (violin plot) of the estimated fixed-base time periods has been compared to the periods identified from the Northridge earthquake response data in Figure 19. Only the EW time period corresponding to the first mode shows a slight change in the superstructure, while the second period does not show any significant changes.

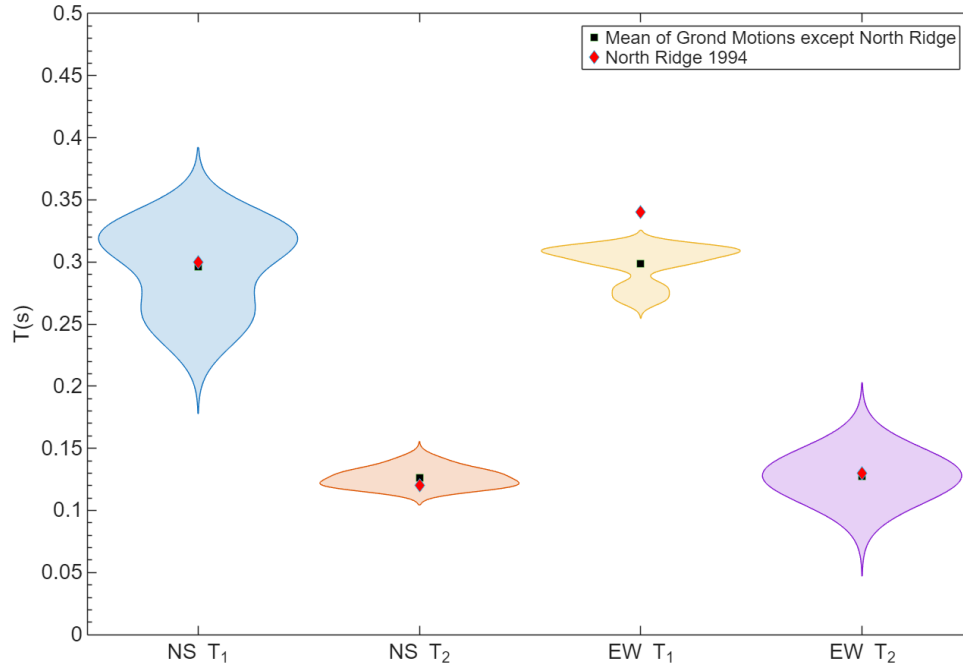


Figure 17: Comparison of fixed-base modal periods from Northridge data with subsequent earthquakes

Conclusions

The seismic response data of the USC hospital and FCC base-isolated buildings, located in the seismically active Los Angeles area, have been analyzed in this study. The dynamic response of the structures to the 1994 Northridge earthquake and subsequent seismic events of lower intensities offers important insights into the structural properties of the buildings.

In the case of the USC hospital building, it is observed that the periods and damping ratios corresponding to the first two base-isolated modes identified from the Northridge earthquake are significantly higher than those identified based on post-1994 datasets. This behavior is expected since the later earthquakes were of much lower intensity than the Northridge earthquake, and therefore, did not fully activate the base-isolation system flexibility past yield. In the Northridge earthquake, the first base-isolated mode shapes indicate larger drift above the isolators, resulting from the activation of the base isolation system's flexibility. Additionally, a slight change in the fixed-base periods of the superstructure is observed in earthquakes after 1994, which may be due to minor stiffness changes.

Similarly, the first base-isolated mode period for the FCC building in both east-west and north-south directions is higher in the case of the Northridge earthquake response (past 16 seconds) compared to the low-intensity ground motions from later years. In the Northridge earthquake, acceleration spikes are evident in the EW direction due to pounding against the entry bridge, which

ceased subsequently past 16 seconds, and the FCC building behaved as a typical base-isolated structure. The negligible change in the fixed-base modes indicates that there has been hardly any change in the FCC superstructure properties over the years. In the FCC building, the time period and damping ratio corresponding to the first base-isolated mode are significantly higher due to the flexibility of base isolation and energy dissipation. The first base isolated mode shapes indicate larger drift above the isolators due to the activation of the base isolation system's flexibility.

In conclusion, it can be inferred that the base-isolation systems for both USC and FCC buildings are in good condition, with no significant changes. The superstructure in the USC hospital building does indicate minor changes in stiffness, but the exact cause for this is difficult to infer. However, in the FCC building, no change in superstructure property is evident.

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