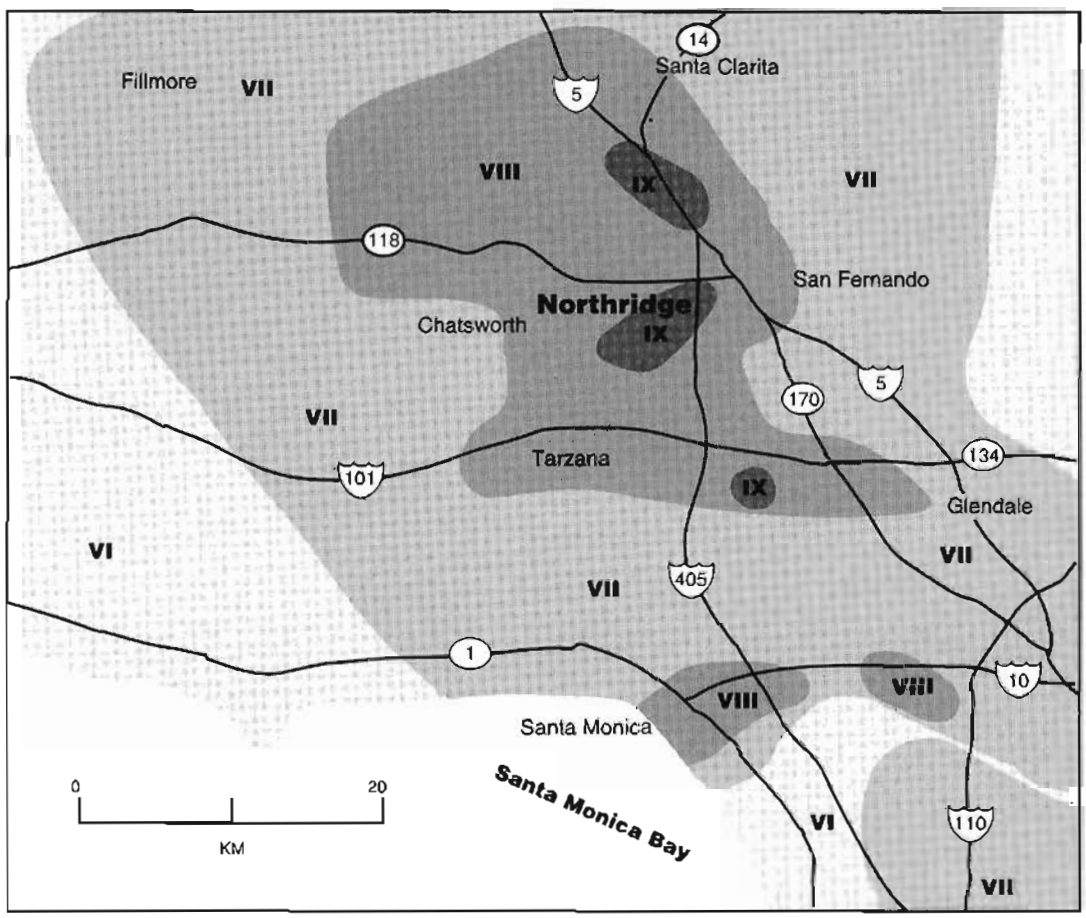
THE CONTINUING CHALLENGE

THE NORTHRIDGE EARTHQUAKE OF JANUARY 17, 1994



Report to the Director,
California Department of Transportation

by the

Seismic Advisory Board

George W. Housner, Chairman

October 1994

THE CONTINUING CHALLENGE

Report on
the Northridge Earthquake
of January 17, 1994

Submitted to the
Director, Department of Transportation
State of California

by the

Seismic Advisory Board

George W. Housner, Chairman
Joseph Penzien, Vice Chairman
Bruce A. Bolt
Nicholas F. Forell
I. M. Idriss
Joseph P. Nicoletti
Alexander C. Scordelis
Frieder Seible

Charles C. Thiel Jr., Editor

October, 1994

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Publications Section
P.O. Box 1015
North Highlands, California 95660, (916) 973-3700

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George W. Housner
Chairman

Three essential challenges must be addressed by the citizens of California, if they expect a safe future from earthquakes:

- Ensure that earthquake risks posed by new construction are acceptable.
- Identify and correct unacceptable seismic safety conditions in existing structures.
- Develop and implement actions that foster the rapid, effective, and economic response to and recovery from damaging earthquakes.

—*Competing Against Time*
Governor's Board of Inquiry on the 1989 Loma Prieta Earthquake

It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings.

—Governor George Deukmejian
Executive Order D-86-90, June 2, 1990

The safety of every Californian, as well as the economy of our state, dictates that our highway system be seismically sound. That is why I have assigned top priority to seismic retrofit projects ahead of all other highway spending.

—Governor Pete Wilson
Opening of the repaired Santa Monica Freeway, April 11, 1994

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Section 1

Overview

Caltrans appointed the Seismic Advisory Board in September, 1990, as directed by Governor George Deukmejian in Executive Order D-86-90, dated June 2, 1990, and in response to recommendations contained in *Competing Against Time: Governor's Board of Inquiry Report on the Loma Prieta Earthquake.* The charge to the Seismic Advisory Board was to provide continued, focused evaluations of Caltrans seismic policy and technical procedures. Since that time, the eight-member Board has regularly reviewed Caltrans seismic design, retrofit, and hazard mitigation activities. The Board also had numerous discussions on the Caltrans program with senior staff engineers and made numerous recommendations.

The Northridge earthquake of January 17, 1994, in the Los Angeles region of California, provided an opportunity for the Seismic Advisory Board to evaluate the performance of Caltrans bridges, retrofit programs, peer review programs, and technical procedures. In response to the Northridge earthquake this report of the Seismic Advisory Board:

- Evaluates the past four years of changes and developments in seismic design criteria and the highway bridge retrofit program.
- Summarizes Board findings on the performance of highway bridges in the Northridge earthquake.
- Recommends improvements to Caltrans bridge seismic design and retrofit programs and procedures.

This section provides an overview of the report. Section 2 gives the detailed findings and recommendations of the Board. The remaining sections and appendices provide the details that led to the Board's findings and recommendations.

Damage to Highway Bridges in the Northridge Earthquake

Caltrans has approximately 12,000 state highway bridges in California and is responsible for a total of 2,523 state and interstate highway bridges in Los Angeles County. Additionally, about 1,500 bridges are maintained by Los Angeles County and 800 by the City of Los Angeles, and most of these latter bridges are small, single span-bridges and most were remote from the area of strong ground motion. Only a few of the city and county bridges were significantly damaged. Sections 3 and 4 provide additional information on bridge performance.

The Northridge earthquake of January 17, 1994 (M_W=6.7; M_W is the moment magnitude) caused the collapse of seven highway bridge structures and the consequent disruption of a large portion of the northwest Los Angeles freeway system. Figure 1-1 shows the locations of these bridges in relationship to the earthquake source. Of the seven bridges that collapsed in the earthquake, five had been scheduled as requiring retrofit. Two bridges, the Mission & Gothic Undercrossing and Bull Creek Canyon Channel on State Route 118, had been identified as not requiring retrofit. The collapsed structures can be classified by vintage into three groups: three bridges designed and built before the 1971 San Fernando earthquake (M_W=6.6); two bridges designed before 1971, but construction completed after 1971; and, two bridges designed and built a few years after San Fernando, but not to current standards.

Many other bridges in the strongly shaken region sustained damage, but did not collapse. The damage ranged from minor

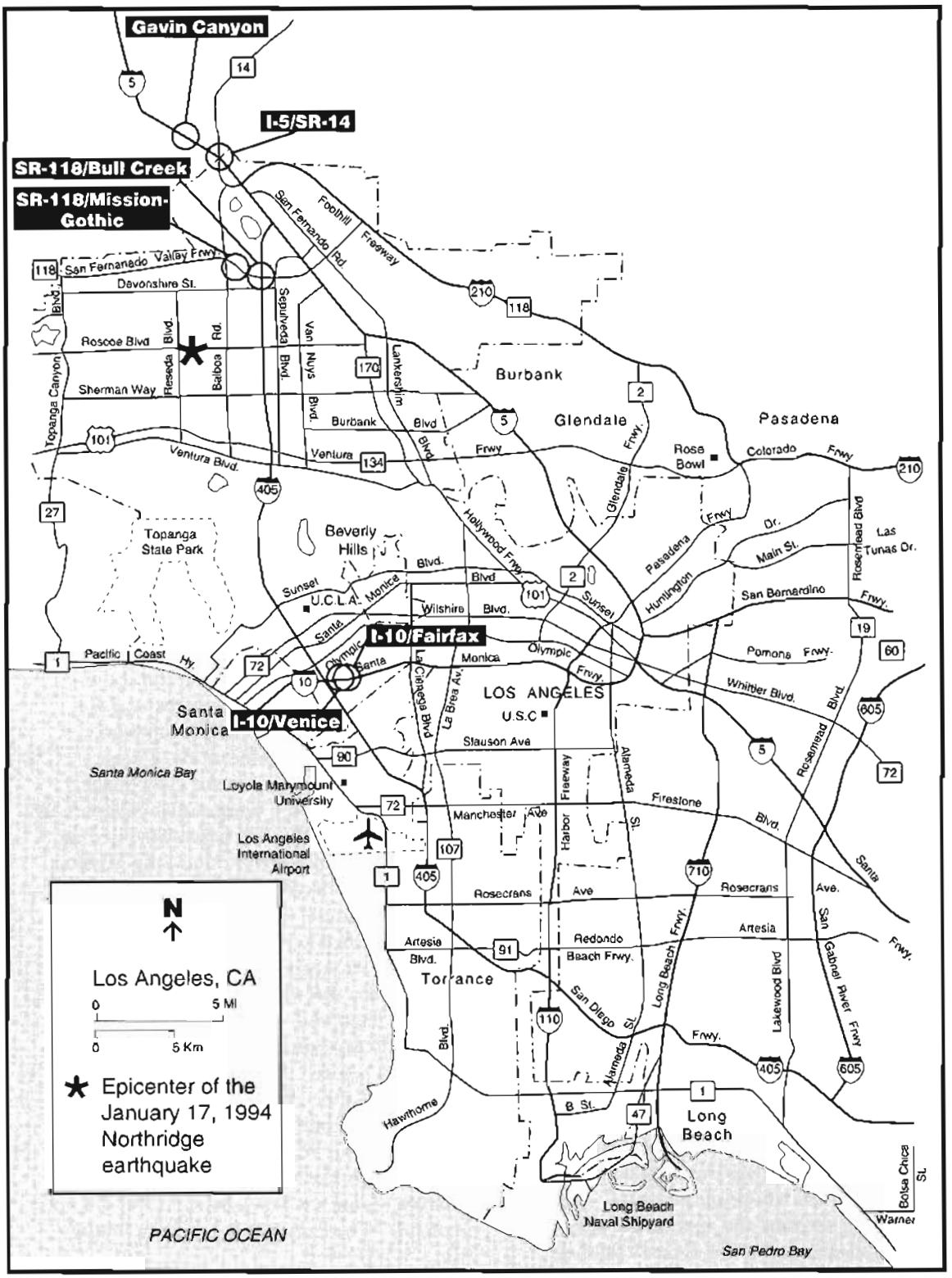

Figure 1-1. *The location of bridges that collapsed in the Northridge earthquake of January 17, 1994; two bridges, the north and south connector overcrossing, collapsed at the I-5/SR-114 Interchange.*

cracking and spalling of concrete to more severe damage that necessitated closing some bridges to traffic while repairs were made.

The bridges in the regions of shaking that were constructed or retrofitted to current Caltrans criteria had, at most, minor damage. All remained in service and none posed a significant safety hazard.

Bridge damage was predictable given the ground motion recorded during the Northridge earthquake. The older bridges were designed for only a small fraction of the ground motion they were subjected to in the Northridge earthquake, and their damage or collapse could be expected. The types of damage observed in the Northridge earthquake are, in the main, consistent with those observed on older bridges in the 1989 Loma Prieta (M_W=7.0), 1987 Whittier Narrows (M_W=5.9), and 1971 San Fernando (M_W=6.6), earthquakes. Appendices C and D contain a discussion of the impacts of the San Fernando and Loma Prieta earthquakes on bridges.

Retrofitted Bridges Performed Adequately

All structures in the region of strong shaking that were retrofitted since 1989 performed adequately, thus demonstrating the validity of the Caltrans retrofit procedures; there were 24 retrofitted bridges in the region of very strong shaking and a total of 60 in the region having peak accelerations of 0.25g or greater. The retrofitted structures resisted the earthquake motions much better than the unretrofitted structures. The Board's conclusion is that if the seven collapsed bridges had been retrofitted, they would have survived the earthquake with little damage.

Caltrans Seismic Design Criteria and Retrofit Program

Caltrans has seismic design performance criteria that set standards for two categories of bridge structures—important and common. Table 1-1 (page 6) reproduces the Caltrans seismic performance requirements. Important structures are those that do not have convenient alternative routes, whose economic consequences of failure are large, or that provide secondary life safety or are designated as important by local emergency officials. Technical evaluations are made for each type for two levels of earthquake ground motions—the functional and safety levels.

For the safety level evaluation, the Board interprets the performance statement as explicitly containing the goal that collapse be avoided in earthquakes for all state bridges, whether new or retrofitted. For the functionality level evaluation, Caltrans has adopted performance criteria that will allow post-earthquake damage inspection and repair with minimal traffic interruptions.

Since the 1971 San Fernando earthquake, Caltrans has been engaged in a multiphase bridge retrofit program. To date most expansion joints have been provided with restrainers or seat extensions and most critical single-column-bent bridges have been retrofitted. Prompted by the 1987 Whittier Narrows earthquake and amplified by the 1989 Loma Prieta earthquake, Caltrans has accelerated the bridge retrofit program and initiated significant changes in bridge design criteria.

Sections 5 and 6 provide more detail on Board suggestions for how the Caltrans seismic program can be improved.

Lack of Progress on Toll Bridges

While there is no doubt that Caltrans has made steady progress in implementing the retrofit program, the Board would like to stress that there are no construction projects underway in the Spring of 1994 for toll bridges, either in southern or northern California. The size and complexity of toll bridges makes progress slower, but their importance puts a premium on completion before they are damaged in an earthquake. Hazard analyses are complete for all 11 toll bridges, and vulnerability analyses have been completed for a few. Preparation of retrofit designs has not yet started for most, and no construction is expected to start for some time. The toll bridge projects need greater emphasis to ensure their timely completion.

Public Concerns and Questions

The Seismic Advisory Board has identified four important questions about the performance of bridges in the Northridge earthquake from those raised by legislators, newspaper reporters, and the public. The questions and Seismic Advisory Board answers are:

1 **Question:** Do the results of the Northridge earthquake indicate that the Caltrans seismic retrofit program has been effective and appropriate?

Answer: Yes, the technical standards appear sound. All 24 of the retrofitted bridges in the region of intense ground motion (PGA≥0.5g) performed well. It is of some concern to the Board that two of the seven collapsed bridges had not been selected for retrofitting; the other five already had been scheduled for retrofit. The screening process used to identify retrofit priorities is evolving and generally sound, but needs improvement. The damage to older bridges was essentially of the same type as observed in California earthquakes during the past 25 years. There was no way to know that the Northridge earthquake could happen before other possible earthquakes that could have occurred at other seismically active sites.

2 **Question:** If the bridges that collapsed had been retrofitted before the earthquake, would they have been protected?

Answer: Yes. Observed performance indicates that the collapse and major damage suffered by highway bridges in this earthquake would have been prevented if the bridges had been built or retrofitted to current Caltrans criteria.

3 **Question:** Is the retrofit program for State of California bridges proceeding at the right pace?

Answer: In part. For single-column-bent bridges, nearly all projects are either completed or under construction. For multiple-column-bent bridges, retrofit construction has been completed for only about 7% of the projects. For toll bridges, few design efforts have begun. The number of bridges that have been retrofitted has been controlled primarily by the availability of resources. The pace could be quickened by resolving the administrative, budgetary, contractual, legal, and personnel constraints that slow progress.

4 **Question:** Do the results of the Northridge earthquake indicate that Caltrans seismic design procedures for new structures need to be modified?

Answer: No. The Board believes that the current design procedures are appropriate. This earthquake was not a complete test, since longer duration ground motions can be expected in future California earthquakes. Nevertheless, the Board believes that if the structures had been designed to current standards they would have sustained little or no damage. The Caltrans procedures are expected to continue to be improved as new information and observed performance become available.

Conclusions

The Seismic Advisory Board concludes that the overall performance of Caltrans structures is consistent with the 1990 directives of the Governor and the Legislature on seismic safety of bridges. The Seismic Advisory Board has witnessed fundamental changes in Caltrans policy since the 1989 Loma Prieta earthquake. Immediately following the Loma Prieta earthquake, the Caltrans approach to the replacement and retrofit designs of bridges could be characterized as uncertain at the design level, while management was pushing forward rapidly. In the Spring of 1994, following the Northridge earthquake, both management and design groups seem to be well-synchronized and acting with confidence.

Observations of bridge performance in the Northridge earthquake lead the Board to conclude that the Caltrans seismic design procedures for new bridges and its retrofit procedures for existing hazardous bridges are technically sound. The Board finds that the retrofit program is proceeding fairly well, but that the screening methods used to identify hazardous bridges could be improved. The major issue where substantial improvements can be made is in the pace of retrofitting the existing deficient bridges and particularly the toll bridges.

Retrofitting of toll bridges is proceeding at a slow pace, limited by budgetary constraints, even though their vulnerabilities are high. It is imperative that retrofitting of toll bridges be funded and implemented without delay. These bridges are too important to the economy of California to be left at risk to earthquake destruction by their current vulnerable states.

The findings and recommendations of the next section, as well as suggestions in Section 6, provide details on how the Caltrans program can be improved.

Although much has been accomplished, much remains to be done. Earthquakes of similar size to the Northridge earthquake, and even larger, will continue to occur in California. With some improvements, the Caltrans program should be continued with dispatch and determination. The major foreseeable impediments to a successful program are inadequate or fluctuating funding.

The Seismic Advisory Board has confidence that the California highway system is progressing in an orderly fashion to one that is significantly more seismically safe. The Northridge earthquake demonstrates that Caltrans retrofit efforts to date have been responsive to the seismic hazard and the engineering approach of the Department of Transportation is fundamentally sound.

Table 1-1. *Caltrans seismic performance criteria and definitions for the design and evaluation of bridges. In the text of this report the term* ***common*** *is used in place of* ***minimum*** *for all those structures that are designated not important by the definition given below.* (Department of Transportation 1994)

Ground Motion at the site	Minimum performance Level	Important bridge performance level
Functional evaluation	Immediate service level; repairable damage	Immediate service level; minimal damage
Safety evaluation	Limited service level; significant damage	Immediate service level; repairable damage

Definitions:

Important bridge: (one of more of the following items present):

- Bridge required to provide secondary life safety (example: access to an emergency facility.)
- Time for restoration of functionality after closure creates a major economic impact.
- Bridge formally designated as critical by a local emergency plan.

Functional evaluation ground motion: Probabilistically assessed ground motions that have a 40% probability of occurring during the useful lifetime of the bridge. The determination of this event shall be reviewed by a Caltrans approved consensus group. A separate Functionality Evaluation is required only for Important Bridges. All other bridges are only required to meet specified design requirements to assure Minimum Functionality Performance Level compliance.

Safety evaluation ground motion: Up to two methods of defining ground motion may be used:

- Deterministically assessed ground motions from the maximum earthquake as defined by the Division of Mines and Geology Open-File Report 92-1 (1992).
- Probabilistically assessed ground motions with a long return period (approximately 1000-2000 years).

For important bridges both methods shall be given consideration, however, the probabilistic evaluation shall be reviewed by Caltrans approved consensus group. For all other bridges, the motions shall be based only on the deterministic evaluation. In the future, the role of the two methods for other bridges shall be reviewed by a Caltrans approved consensus group.

Immediate service level: Full access to normal traffic available almost immediately.

Repairable damage: Damage that can be repaired with a minimum risk of losing functionality.

Limited service level: Limited access (reduced lanes, light emergency traffic) possible within days. Full service restoration within months.

Significant damage: A minimum risk of collapse, but damage that would require closure for repairs.

Section 2

Findings and Recommendations

The Seismic Advisory Board bases the following findings and recommendations on its analysis and review of the Northridge earthquake's impacts on transportation structures, the Caltrans retrofit program, Caltrans response to the recommendations contained in *Competing Against Time: The Governor's Board of Inquiry Report on the Loma Prieta Earthquake, May 1990*; directions given by Governor Deukmejian's Executive Order D-86-90, dated June 2, 1990; and to the requirements of Senate Bills 36X and 2104. The basis for these findings and recommendations can be found in the balance of the report.

The Seismic Advisory Board recommends that the indicated actions be undertaken on a priority basis.

Bridge Performance in the Northridge Earthquake

1 **Finding:** Caltrans has 12,176 state bridges and of these 9,206 were designed prior to the engineering impact of the 1971 San Fernando earthquake. At this time, knowledge of destructive earthquakes and the seismic performance of structures was in an undeveloped state so that bridges designed prior to the San Fernando earthquake were not up to current standards of seismic design and it was known since the San Fernando, Whittier, and Loma Prieta earthquakes that some of these structures could not survive intense ground shaking. Examples are the Nimitz Freeway double-deck viaduct that collapsed in the 1989 Loma Prieta earthquake and the bridges that collapsed in the Northridge earthquake.

2 **Finding:** Damages observed in the Northridge earthquake are, in the main, consistent with those observed in the 1989 Loma Prieta, 1987 Whittier Narrows, and 1971 San Fernando earthquakes.

3 **Finding:** The Northridge earthquake provided a valuable test for Caltrans design procedures in high-intensity, moderate magnitude earthquakes, but did not constitute a test of their behavior in the larger, long-duration earthquakes that are expected to occur in the future.

4 **Finding:** Of the seven bridges that collapsed, five had been identified and scheduled for seismic retrofit. Two, the Mission & Gothic Undercrossing and the Bull Creek Canyon Channel Undercrossing on State Route 118, had been evaluated as not high-risk and were not scheduled for retrofit.

Recommendation: Caltrans should evaluate those bridges that were not included in the first retrofit group to determine if they require retrofitting. The evaluation should be performed with the essential objective of collapse avoidance in all earthquakes.

5 **Finding:** The performance of recently retrofitted bridges in the Northridge earthquake appear to be acceptable. The evolving post-Loma Prieta earthquake design and retrofitting practices used by Caltrans appear to be sound. No significant damage has been reported to the 60 bridges retrofitted by Caltrans in the region of strong shaking since the start of the post-1987 retrofit program. Prior to 1987, the retrofit approach was to

use expansion joint restrainers only. Performance of joint restrainers in the Northridge earthquake was mixed. While retrofitted bridge performance in this event was acceptable, evaluation of the expected performance of these bridges in other earthquakes with greater durations may reveal opportunities for improvement.

Recommendation: A thorough study of the performance of bridges in the Northridge earthquake should be conducted to determine if changes in Caltrans design practices and priority setting procedures are needed. This should be completed through in-house and independent, external studies, as appropriate. Bridges of both concrete and steel should be studied.

6 **Finding:** The public can have confidence in the seismic safety of the Northridge earthquake replacement structures because they are being well designed and peer reviewed.

Retrofit Program

7 **Finding:** Caltrans has made acceptable progress in implementing the retrofit program of single-column-bent bridges, with construction either begun or completed on 100% of the identified bridges. In addition to retrofitting the single-column-bents, the program includes retrofitting the abutments and footings as needed. For the multiple-column-bent bridges, the retrofit program has been completed for only about 7% of the projects. It has made slower progress on toll bridges, where vulnerability studies are only now being initiated on some, and construction is not underway on any.

Recommendation: Caltrans should identify the most hazardous highway bridges in the State and fully retrofit them as quickly as practical, instead of approaching the retrofit programs by category of structures.

Recommendation: More emphasis must be given to starting toll bridge retrofit construction projects on as rapid a schedule as practical.

8 **Finding:** The priority setting process used by Caltrans, and as reviewed by the Seismic Advisory Board, involves classifying structures by vulnerability, seismic hazard, and impact on the community. Each category has several elements, some of which do not now appear to be weighted appropriately (for example, soil conditions at the site and the system response of interconnected bridges, such as the sequence of bridges on the Santa Monica Freeway). The present process yields priority lists determined by calculations that do not take into account all important factors affecting seismic safety.

Recommendation: The Caltrans prioritizing procedure should be reviewed and modified based on current understanding. Attention should be given to the quality of information used in the process, including the presence of nonductile columns, variable soil conditions, and the effect that a series of bridges has on the vulnerability of a freeway as an interconnected system. Other characteristics and their weightings should also be re-examined.

Design

9 **Finding:** Caltrans design procedures have two performance categories: important and common. The performance objective for important bridges is to have full access available to normal traffic almost immediately following a major earthquake. The performance criteria for all common bridges in a major earthquake are to avoid collapse, but to allow significant damage and limited service. While any of three characteristics—secondary safety, economic impact or emergency use—can lead to classification as "important," there is some ambiguity in the specific characteristics that make a bridge important. The public's response to the Northridge earthquake suggests that more bridges should be classified as important than the current procedure yields.

Recommendation: Caltrans should reconsider and broaden the definition of an *important* structure and the appropriate performance objectives for both important and common bridge categories. Concurrently, the acceptance criteria, or limit states, leading to each performance objective should also be defined.

10 **Finding:** The Northridge earthquake occurred on a previously unidentified blind thrust fault, a type of fault that does not have a surface trace. The possibility of blind-thrust earthquakes was well recognized by both the technical community and Caltrans. The Northridge earthquake produced ground motions that were high, but within the range considered possible. With few exceptions, vertical accelerations were not unusually high compared to horizontal accelerations.

Recommendation: Future seismic hazard assessments should consider the likelihood of blind thrust faults.

11 **Finding:** The duration of the strong velocity pulse observed in near field time history recordings during the Northridge earthquake once again affirms its importance to design. It occurs at sites near fault ruptures and above thrust faults. The possibility of a velocity pulse at a site should be given consideration for near field sites in the design of bridges, especially when assessing non-linear response.

Recommendation: The Caltrans bridge design procedures should be assessed, and revised as required, to determine if they adequately reflect the structural demands caused by velocity pulses.

12 **Finding:** The seismic hazard used in the design of common bridges is based only on deterministic evaluations for the maximum earthquakes that can occur throughout the state as prepared by the California Division of Mines and Geology (CDMG). There is some debate as to how these earthquakes and the faults on which they occur should be selected and what attenuation relationship should be used to determine the best estimate of ground motions at a site. The current map only reflects mean peak ground motion estimates; it does not include duration effects or velocity pulses, both of which may be important for common bridge design.

Recommendation: Caltrans should reconsider the technical assumptions leading to the deterministic map and prepare a new one to reflect current understanding of both seismic hazard and the way in which these values are used in bridge design.

13 **Finding:** Caltrans has several hundred steel girder bridges in California. A number of these in the San Fernando Valley area were subjected to strong shaking and sustained severe damage to the end bearings and to the bearing supports. None of these bridges collapsed but at the end of the earthquake they were in a potentially hazardous condition.

Recommendation: Caltrans should investigate the support systems for steel girder bridges and strengthen them as required.

14 **Finding:** Unusual damage was reported to some steel girder bridges. At this writing, two skew bridges have been identified in the region of strong shaking as having cracking in girder webs near welded stiffener plates.

Recommendation: Caltrans should very carefully check all steel bridges and elements in the region of strong shaking to determine if there has been damage. Bridges outside this area throughout the state should be checked for the possibility of having cracks caused by fatigue.

Caltrans Management Actions

15 **Finding:** Caltrans has followed the directions of the Governor based on *Competing Against Time* and the directions of the Governor's Executive Order. Administratively, and in practice, Caltrans is committed to producing seismically safe transportation structures.

Recommendation: Caltrans should continue its commitment to improving the seismic safety of the state's highway bridges.

16 **Finding:** Peer review of the design of new and retrofit bridges has been implemented for complex structures. Peer review is not being conducted for the more prevalent common types.

Recommendation: The scope of projects that are peer reviewed should be extended to include a few representative projects for the more common, prevalent types of structures to validate the design and/or retrofit approach.

17 **Finding:** There is considerable variation in how peer review has been implemented for different structures.

Recommendation: Peer review should be standardized in terms of: 1) which bridges are to be scrutinized; 2) the scheduling of the review to allow designers time to modify the design in response to reviewer comments; and, 3) how complete the peer review should be, ranging from the initial strategy and type selection to the final seismic design detailing. The specific terms of content and format should *not* be standardized—they must be project-specific.

18 **Finding:** Strong motion records were obtained from only six bridges located 14 to 115 miles from the epicenter. None of the bridges that collapsed or had substantial damage were instrumented, thus denying the opportunity to evaluate the effectiveness of design and analysis procedures by comparison with actual response.

Recommendation: Both Caltrans and the California Strong Motion Instrumentation Program must make a greater commitment to installing instruments on bridges, especially toll bridges. Engineers must have recordings from bridges and their sites subjected to high-level ground motions to advance the state-of-the-art in bridge design and analysis.

State Actions

19 **Finding:** The basic and applied research findings and knowledge that have allowed the development of improved seismic design procedures and practices for bridges have come from research on all types of structure and conditions. The continued development of effective seismic design and retrofit procedures for bridges will depend on knowledge generated in many areas of earthquake engineering.

Recommendation: Caltrans should continue its vigorous program of research and development for bridges.

20 **Finding:** Budgetary, administrative, legal, and personnel constraints are the primary reasons why the Caltrans hazardous-bridge retrofit program had not accomplished as much as desirable prior to the Northridge earthquake. In the past, limitations on budget and personnel were the principal drawbacks. Now the issues are: 1) the number of people assigned and their skill levels; 2) the ability of management to contract with qualified engineers to develop designs; and, 3) the ability to initiate construction contracts. Caltrans is working near the limit of what can be realistically done with their current personnel levels and procurement limitations.

Recommendation: If the public wants safer bridges faster than at the current pace, then it will have to provide greater resources, including both administrative and personnel needs, and resolve the legislative, legal, and administrative impediments to implementing retrofit projects quickly.

21 **Finding:** The two collapsed bridges on the Santa Monica Freeway (I-10) were removed, new spans were constructed, and normal traffic flow was established by May 20. This rapid replacement of the damaged bridges was accomplished by means of special contractual arrangements that provided incentives for completion ahead of schedule and disincentives for completion behind schedule. Similar contractual arrangements were made for the completion of all seven collapsed bridges, and Caltrans plans to have them replaced by the end of 1994. This rapid recovery of the heavily traveled Los Angeles freeway system sets a valuable precedent.

Conclusions

The Board concludes that the public should have confidence that new and recently retrofitted structures are being designed and constructed based on sound engineering principles that incorporate the latest research findings and technical knowledge. The public should have confidence that Caltrans is working diligently and with deliberate speed to retrofit hazardous bridges. Retrofit prioritization procedures need to be reexamined, possibly leading to greater emphasis on retrofitting important toll bridges. On the basis of observations in the Northridge earthquake, the seismic vulnerability of California's highway structures is significantly decreasing with time.

Retrofitting of toll bridges is proceeding at a slow pace, limited by budgetary constraints, even though their vulnerabilities are high. It is imperative that retrofitting of toll bridges be funded and implemented without delay. These bridges are too important to the economy of California to be left at risk to earthquake destruction by their current vulnerable states.

The balance of this report provides the technical observations and evidence that the Board used to reach its findings and formulate its recommendations.

Section 3

The Northridge Earthquake and Bridge Performance

The Northridge Earthquake

The Northridge earthquake of January 17, 1994, strongly affected the northern parts of Los Angeles and the San Fernando Valley and surrounding areas in southern California. It was the most costly single natural disaster in the history of the United States. This magnitude 6.7 earthquake occurred at 4:31 am local time on a Monday, and resulted in about 65 deaths and over 5,000 injuries. Preliminary damage estimates are in the range of $15-30 billion.

The earthquake occurred in a highly-populated, urban area. Most affected structures were built in this century. The earthquake caused serious damage and failures in commercial and residential buildings, destruction of the contents of many structures, damage to critical transportation systems, and widespread disruption of utilities and other lifelines. Of great public concern was the collapse or partial collapse of seven bridges of the freeway system (Figure 1-1). In part because of the time of occurrence, only one life was lost from these bridge collapses.

The 1994 Northridge earthquake was in an urban area containing structures of many types. It provided a first test for many modern seismic design practices. Many of these appear to have been very successful, but some now appear to be questionable. The damage to steel bridges and recently completed steel-braced and welded moment frame buildings was unexpected. Recently-constructed bridges and post-1987 retrofitted reinforced concrete bridges, on the other hand appeared to perform reasonably well.

Seismological Characteristics and Ground Motion

The January 17, 1994, main shock of the Northridge earthquake was generated beneath the San Fernando Valley near Northridge at a focal depth of about 18 km. It occurred on a blind thrust fault and thus the principal rupture did not break the surface. Figure 3-1 shows the distribution of Modified Mercalli Intensities (MMI), giving a sense for the shaken areas. It is of interest that within intensity VII zone, pockets of intensity VIII are mapped south of the Santa Monica Mountains.

Since the 1987 Whittier Narrows earthquake, the occurrence of blind-thrust fault earthquakes through the Los Angeles and San Fernando Valleys has been widely accepted, with the likelihood of earthquakes of magnitudes about 6.5 generated by slip on them. In this sense, the type of faulting which produced the Northridge earthquake was not unexpected. The exact position of the causative fault, however, was not predicted. The intensity of shaking appeared to be systematically somewhat higher than expected, based on average attenuation curves for past California earthquakes. Nevertheless, the majority of ground motions fell within the 84% expectation levels (mean plus one standard deviation) and would thus be accommodated by present probabilistic methods of seismic motion assessment. Apart from a few anomalous sites, contrary to some public impressions, the measured peak vertical accelerations (as compared to the observed horizontal values) were also in the expected range of values.

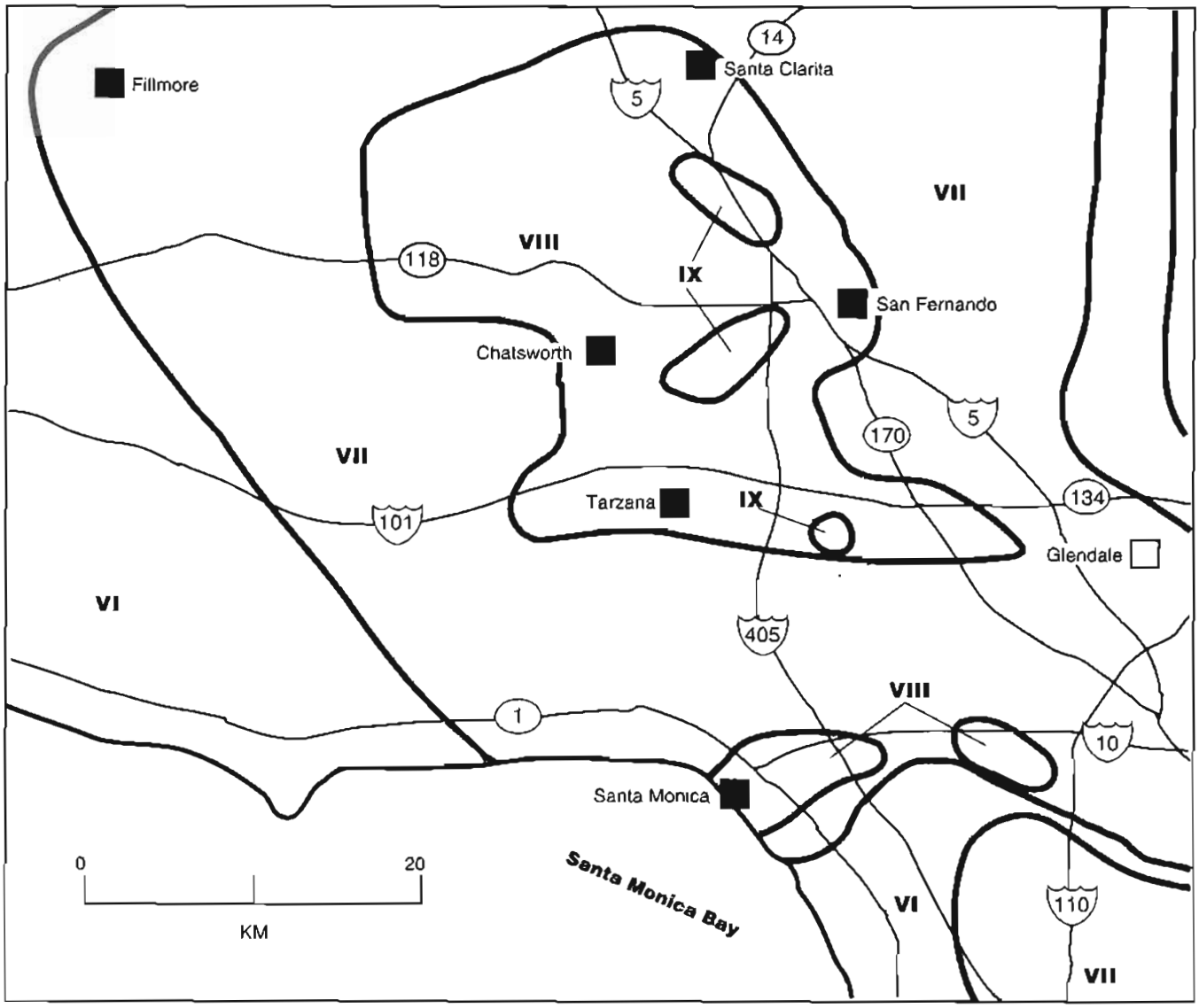

Figure 3-1. *Isoseismal map of the Modified Mercalli Intensities for the Northridge earthquake. The locations of principal highways is indicated for the region of strong shaking. MMI VI is termed moderate and is described by the types of effects observed: felt by everyone; many people are frightened, some run outdoors; small objects fall off shelves; pictures fall off walls; plaster cracks; weak masonry buildings crack. MMI VII is termed strong: weak unreinforced buildings damaged; unreinforced masonry chimneys broken at roof lines; disruption of building contents; plaster cracked. MMI VIII is termed very strong shaking: damage to nonearthquake-resistant structures can be significant, with some collapses, particularly those in poor condition; damage to nonstructural elements in modern, seismically resistant buildings; and substantial disruption of building contents and toppling of unanchored equipment. MMI IX is termed violent: general panic; damage to well-built structures; much interior damage, frame structures are racked and, if not bolted down, shift off foundations; poor quality unreinforced masonry destroyed; well constructed reinforced masonry is seriously damaged; damage to foundations. The assigned intensity values are based on qualitative observations of damage, not recorded ground motions.* (USGS, 1994)

Numerous strong motion instruments had been placed by the California Strong Motion Instrumentation Program (CSMIP) and the U.S. Geological Survey. One-hundred and thirty-two instruments within a 100-mile radius of the fault rupture area recorded the free-field, strong ground motions [Shakal et al, 1994; USGS, 1994]. These records show that:

- Duration of strong motion was about 9 seconds.
- With few exceptions, peak ground motions recorded were within the statistical ranges expected for such an earthquake.
- Ratios of vertical to horizontal peak ground accelerations were typical of past earthquakes, averaging about 2/3.

Strong motion records were obtained from six bridges at distances ranging from 14 to 115 miles. The most significant of

these was the record from the I-10/I-405 Interchange, a curved concrete box girder structure, 1,037 feet long having nine single-column bents and two open-seated abutments. The bridge was retrofitted in 1991 with steel jackets on some columns. Installation of instruments was completed, funded by Caltrans, just before the earthquake. A peak acceleration of 1.83g was recorded at the box girder near the west abutment. This bridge is located about 4 miles west of the section of the I-10 Freeway that collapsed.

Appendix B provides more detail on the seismological and strong motion characteristics of the Northridge earthquake.

Caltrans Seismic Risk Map

The Caltrans seismic criteria use two different methods for defining the Safety Evaluation ground motion (see Table 1-1):

- Deterministically assessed ground motions for the maximum earthquake as defined by the Division of Mines and Geology Open-File Report 92-1 (CDMG 1992).
- Probabilistically assessed ground motions with a long return period (approximately 1000-2000 years).

For important bridges both methods are given consideration. However, the probabilistic evaluation is expected to be reviewed by a Caltrans approved consensus group.

For common bridges, most bridges in the state system, the motions are based only on deterministic evaluations. Figure 3-2 shows the Los Angeles region portion of this deterministic CDMG prepared map. Both peak ground acceleration and locations of specific faults and their maximum credible earthquakes are indicated. The map shows that the epicentral area for the Northridge earthquake had bridge design values of the order of .6g and .5g, higher than the .4g value used in the building codes for the extended Los Angeles region. Comparison of these numbers for bridges and buildings should be done carefully. Compared to typical buildings, bridges have relatively small safety factors. Buildings have substantial redundancies in load paths, so that if one load path is seriously damaged, others can carry the seismic and gravity load. They also have many nonstructural systems, that, while not included as part of the seismic resistance system, do participate in the seismic response providing added capacity. Bridges tend to have very low redundancies, since there are a limited number of columns (often only one) and no non-structural elements to participate in the seismic response. Therefore, even though bridges may use a higher seismic ground motion they may not yield better behavior than a building designed to a lesser value.

The CDMG peak rock acceleration map, Figure 3-2, reflects the mean (best estimate) ground motions from a selected group of known faults. There is some debate as to how these faults should be selected and what attenuation relationship should be used to determine the best estimate rock motions at a site. The map only reflects mean peak rock motion estimates; it does not include duration effects or velocity pulses, both of which may be important for common bridge design. The Board urges that: 1) special care be given in the use of this map; and 2) Caltrans should reconsider the technical assumptions leading to the deterministic map and prepare a new one to reflect current understanding of both seismic hazard and the way in which these values are used in bridge design.

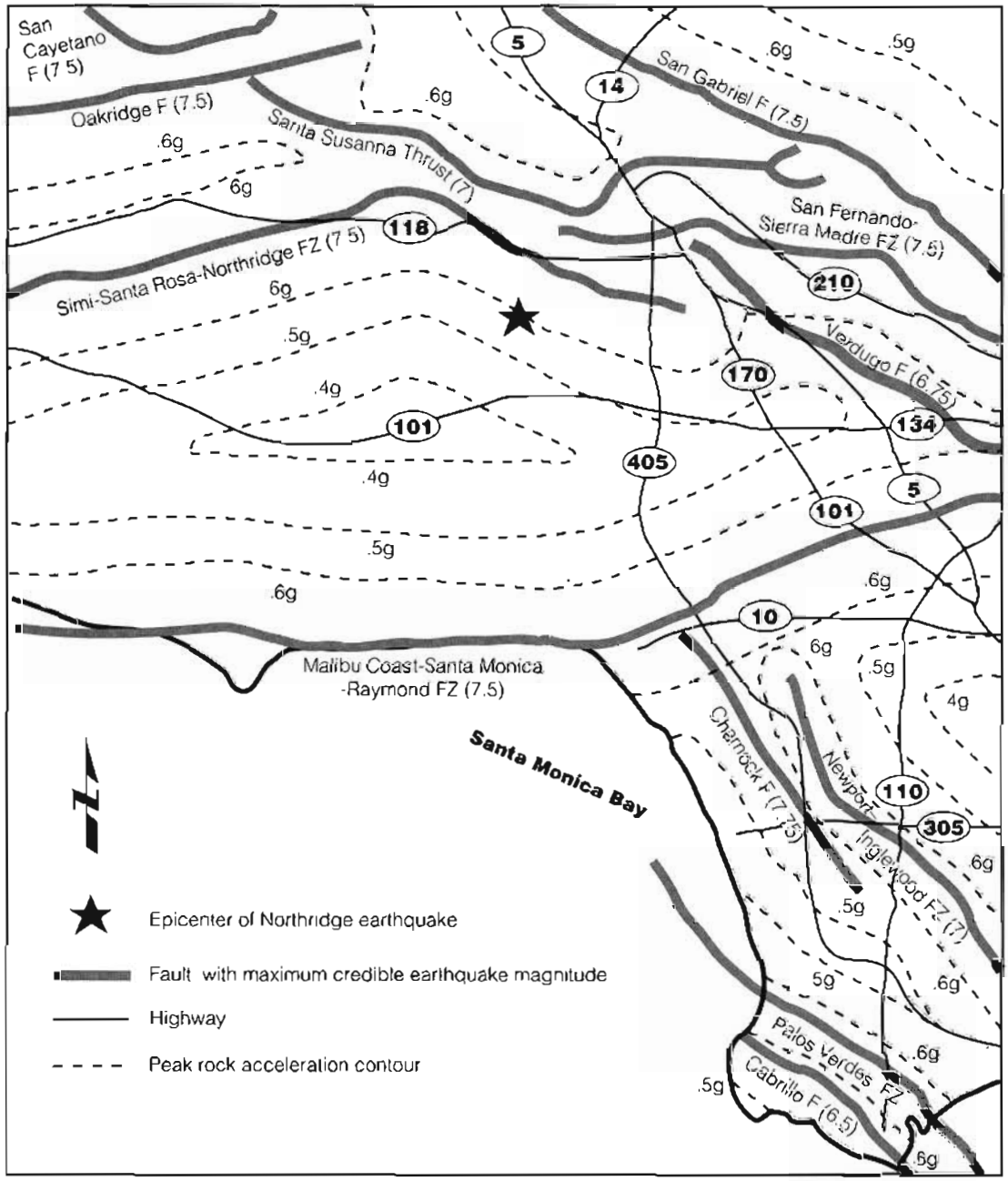

Figure 3-2. *Caltrans peak rock acceleration map showing the seismic mean-acceleration values used for bridge design. Both peak rock acceleration and locations of specific faults and their maximum credible earthquakes are indicated.* (CDMG and Caltrans, 1992)

Summary of Damage to Highway Bridges in the Northridge Earthquake

Caltrans is responsible for a total of 2,523 state or interstate highway bridges in Los Angeles County. Additionally, about 1,500 bridges are maintained by Los Angeles County and 800 by the City of Los Angeles. Only a few of the City and County bridges were significantly damaged. Most of these latter bridges are small, single span bridges and most were remote from the area of strong ground motion.

The Northridge earthquake of January 17, 1994 caused the collapse of seven highway bridge structures (Figure 1-1) and the disruption of a large portion of the northwest Los Angeles freeway system. The collapsed structures can be classified by vintage into three groups: bridges designed and built before the 1971, San Fernando earthquake;

Table 3-1. *Summary of highway bridge collapses in the Northridge earthquake.*

Bridge	Route	Bridge number	Design	Construction completion	Restrainer retrofit	Probable cause of collapse
Gavin Canyon Undercrossing	I-5	53-1797 P/L	1964	1965	1974	Skew geometry and unseating of expansion joints
N. Connector Overcrossing	SR-14/I-5	53-1964 F	1968	1974	1974	Short column brittle shear failure
S. Connector Overcrossing	SR-14/I-5	53-1960 F	1968	1974	1974	Short column shear failure
Mission & Gothic Undercrossing	SR-118	53-2205	1973	1976	—	Flexure/shear failure in architectural flared columns at bottom of flare
Bull Creek Canyon Channel Undercrossing	SR-118	53-2206	1973	1976	—	Flexure/shear failure in shortened columns by channel wall and low transverse reinforcement ratio
Fairfax & Washington Undercrossing	I-10	53-1580	1962	1964	1974	Flexure/shear failure of short and stiff columns
La Cienega & Venice Undercrossing	I-10	53-1609	1962	1964	1978	Brittle shear failure of stiff columns

bridges designed before 1971 but constructed shortly after 1971; and, bridges designed and built a few years after San Fernando, but not to current standards.

Bridge damage was predictable given the ground motions recorded during the Northridge earthquake. The older bridges were designed for only a small fraction of the ground motions they were subjected to in this earthquake, and their damage or collapse was inevitable. The many bridges in the regions of strong shaking that were constructed or retrofitted to current Caltrans criteria had, at most, minor damage; and all remained in service and none posed an increased safety threat during the earthquake.

Information published by Caltrans identifies earthquake damage to State Highway bridges in the Los Angeles County as follows:

1. **Initial Assessment Dated January 21, 1994:** Significant bridge damage occurred within an area of about 270 square miles, as shown in Figure 3-1. A total of 506 Caltrans bridges are located within this area. The reported damage was:

Collapsed or partly collapsed	7
Major damage	4
Moderate damage	2
Minor damage	18

No damage was reported to post 1987 retrofit or new construction. Damage occurred primarily in older structures designed prior to the 1971 San Fernando earthquake that were not retrofitted or had only partial or inadequate retrofits. An exception to the above is the partial collapse of two 1976-vintage bridges on State Highway 118 in the epicentral area.

2. **Detailed Assessment Dated February 9, 1994:** This later, and more detailed, assessment of State Highway bridge damage by Caltrans lists the following:

Collapsed or partly collapsed	7
Major damage	39
Other damage requiring repair	194
Hinges requiring repair or replacement	46

Table 3-1 lists the seven major bridges that collapsed during the Northridge earthquake, along with the date of their design and construction and the probable cause of failure. All seven were constructed to design standards that were much less stringent than those Caltrans currently uses. Section 4 discusses in detail how the bridges performed and current thinking as to why they failed.

Table 3-2. *Comparison of the average daily traffic volumes on the damaged highways before the Northridge earthquake with the corresponding daily traffic volumes on February 4, 1994. The percentage is the ratio of post-earthquake daily traffic volume to pre-earthquake traffic volume.*

Route	Location	No. of Lanes	Normal	Pre-EQ Jan. Avg.	2/4/94	Percent
5	South of Rte 170	8	151,000	156,880	149,663	95%
10	East of Rte 405	8	267,000	267,273	113,029	42%
101	West of Rte 405	10	275,000	309,049	267,371	87%
105	East of Rte 405	8	N/A	171,135	186,234	109%
118	West of Rte 405	8	139,000	125,279	48,532	39%
134	East of 101/170 IC	8	200,000	197,973	264,909	134%
170	North of Rte 101-SE only	4	177,000	78,058	76,143	98%
405	North of Rte 10	10	274,000	271,940	234,834	86%
405	South of Rte 10	10	316,000	321,694	298,851	93%

Many other bridges in the strongly shaken region sustained damage, but did not collapse and remained in service, either full or limited. The damage ranged from minor cracking and spalling of concrete to more severe damage that necessitated closing the bridge to traffic while repairs were made.

Impact on Traffic Flow in Los Angeles County

Immediately following the Northridge earthquake, Caltrans moved quickly to mobilize construction equipment and personnel to remove debris and restore or reroute traffic where damage had occurred to the highway system.

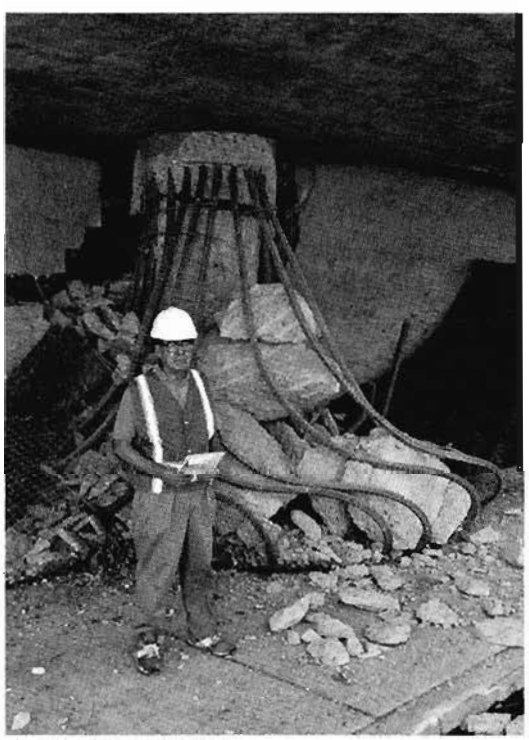

Figure 3-3. *Bridge piers with completely disintegrated core, ruptured hoop reinforcement, and buckled longitudinal reinforcement.* (photo: F. Seible)

The failure of the bridges listed in Table 3-1 caused substantial rerouting of traffic. Table 3-2 identifies the damaged state highways in the county and their average daily traffic volumes before the earthquake and on February 4, 18 days after the earthquake. Traffic records for each of 10 days preceding February 4, show that the average delay on each route decreased as alternate routes were opened and drivers became accustomed to changed highway conditions. As of February 4, 1994, the delays ranged from 2 to 25 minutes, many times less than the initial delay times, which had been as much as 2 hours. These travel time reductions indicate that, while it may require considerable time before the collapsed bridges are replaced, Caltrans has established effective detours, and, except for State Routes 10 and 118, traffic flow was essentially restored to normal volumes within a few weeks.

Seismic Advisory Board Field Trip to Damaged Structures

On January 22, 1994, the Seismic Advisory Board visited the four major bridge collapse sites: the I-10 Santa Monica Freeway, the SR-118 Simi Valley-San Fernando Freeway, the I-5/SR-14 Antelope Valley Interchange, and the I-5 Gavin Canyon Undercrossing. Numerous other trips were made by individual Board members.

Figure 3-4. *Steeply inclined shear cracks and cover spalling in one bent at Fairfax & Washington on I-10* (photo. F. Seible)

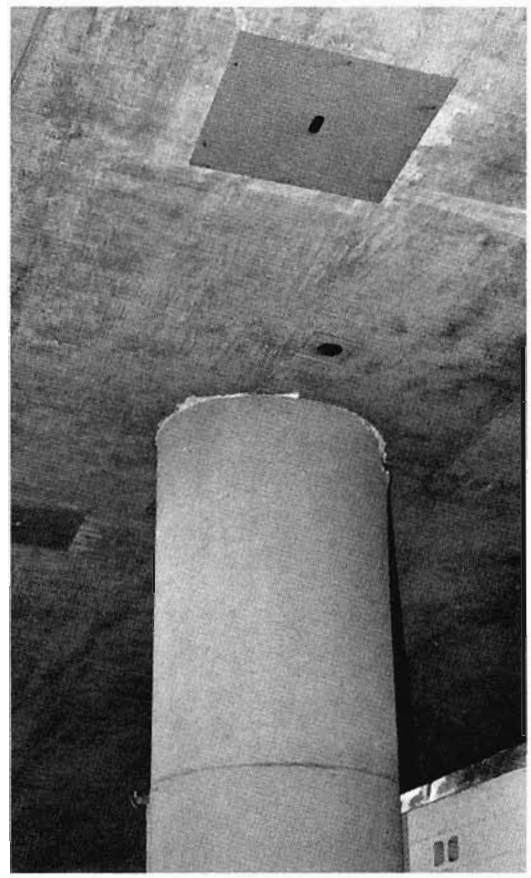

Figure 3-5. *Flexural cracks at the column ends in the adjacent bent at Fairfax & Washington on I-10.* (photo: F. Seible)

At all bridge collapse sites, five days after the earthquake, removal of the collapsed bridge structures was either in progress or already completed where roadway access was necessary. However, damage patterns and critical failure modes were still visible in adjacent bridge sections.

At the I-10 La Cienega and Venice site, bridge piers with completely disintegrated core, ruptured hoop reinforcement, and buckled longitudinal reinforcement suggest the explosive or brittle failure mode of some of these columns (Figure 3-3). Section 4 provides more information on the collapse of this and other major bridges discussed below.

At Fairfax & Washington on I-10, steeply inclined shear cracks and cover concrete spalling (Figure 3-4), and flexural cracks at the column ends in the adjacent bent (Figure 3-5), clearly show the influence of column height and boundary conditions, with the shorter columns fixed at both ends showing the critical shear failure patterns. Columns retrofitted with circular steel jackets (Figure 3-6), at the Cadillac Avenue off ramp directly adjacent to Washington and Fairfax showed only minor cracking and

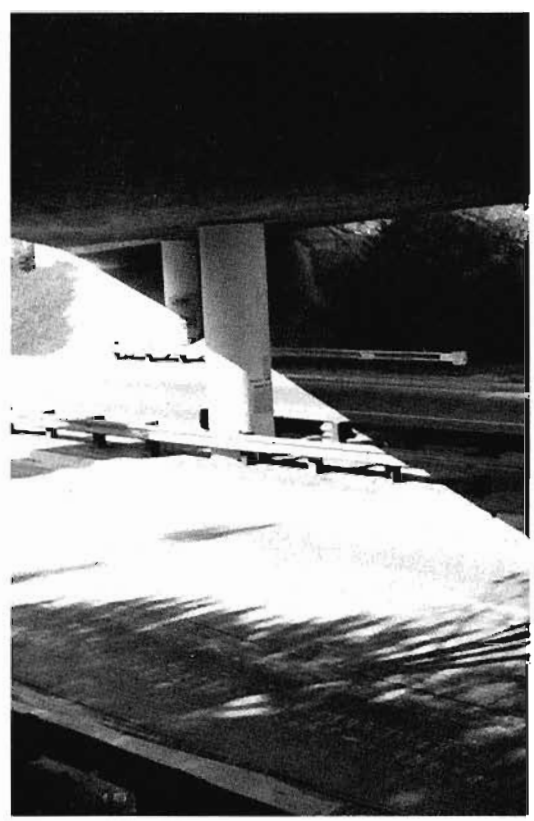

Figure 3-6. *Columns retrofitted with circular steel jackets at the Cadillac Avenue offramp directly adjacent to Washington and Fairfax. These columns survived without problems the same ground accelerations that caused the Washington and Fairfax collapse (Figures 3-4 and 3-5).* (photo: F. Seible)

Figure 3-7. *Flexure/shear failure in the bottom of the flared columns still visible in the westbound bridge, even though demolition was in full progress at the SR-118 Mission & Gothic Undercrossing.* (photo: F. Seible)

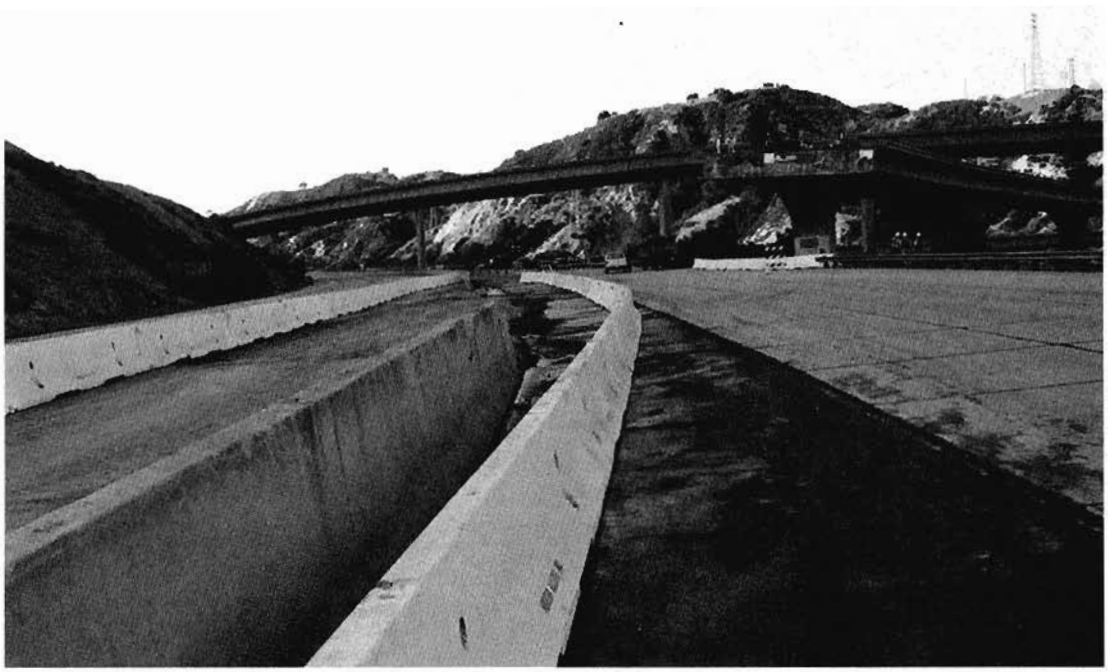

Figure 3-8. *Completed demolition of the southbound connector at the Antelope Valley I-5/SR-14 Interchange five days after the earthquake* (photo: F. Seible)

spalling in the joint between the steel jacket and the bottom soffit. These retrofitted columns survived, without signs of damage, the same ground accelerations that caused the Washington and Fairfax columns to collapse.

At the Simi Valley-San Fernando SR-118 Freeway, the flexure/shear failure mode in the flared columns at the bottom of the flares was still visible in the westbound bridge, even though demolition was in full progress at the SR-118 Mission & Gothic Undercrossing for the eastbound structure, see Figure 3-7.

At the Antelope Valley I-5/SR-14 Interchange, demolition of the collapsed portions of the south and north connectors was already completed (Figure 3-8), but abutment and expansion joint damage in the separation structures provided a graphic reminder of the encountered force and displacement levels (Figures 3-9 and 3-10).

Finally, at I-5 Gavin Canyon, the collapsed section of the bridge structure had been removed, but the highly skewed geometry and narrow joint seat width was evident from the still-standing center frame (Figure 3-11).

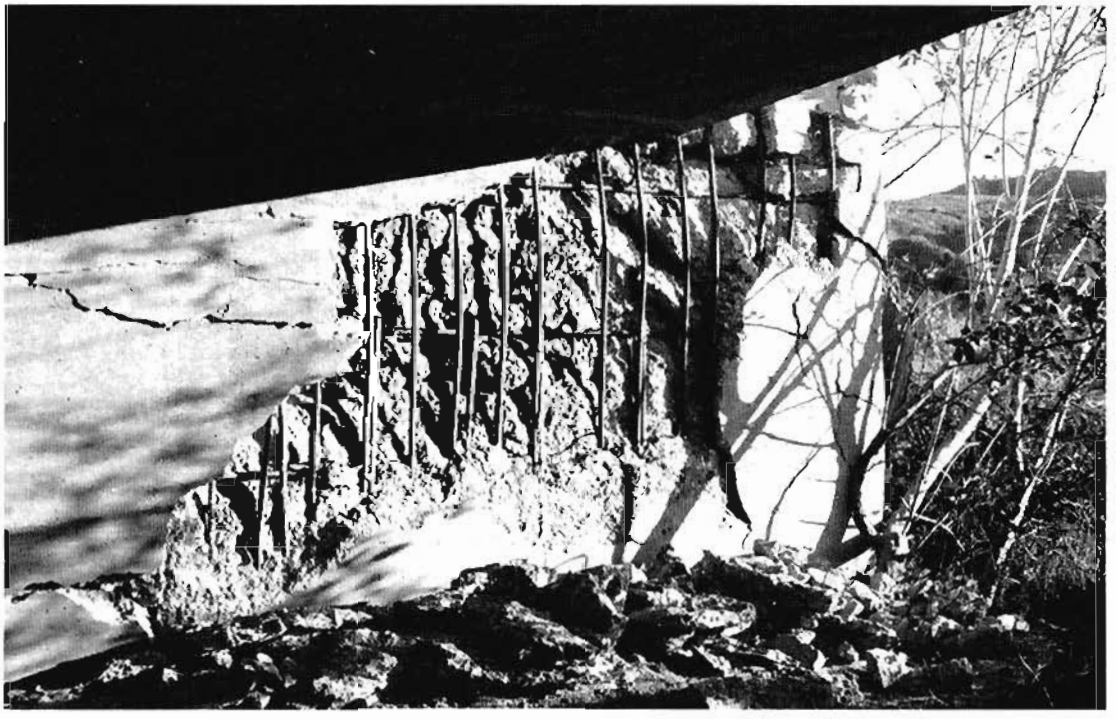

Figure 3-9. *Abutment joint damage in the separation structures at the Antelope Valley I-5/SR-14 Interchange* (photo: F. Seible)

Figure 3-10. *Expansion joint damage in the separation structures at the Antelope Valley I-5/SR-14 Interchange* (photo: F. Seible)

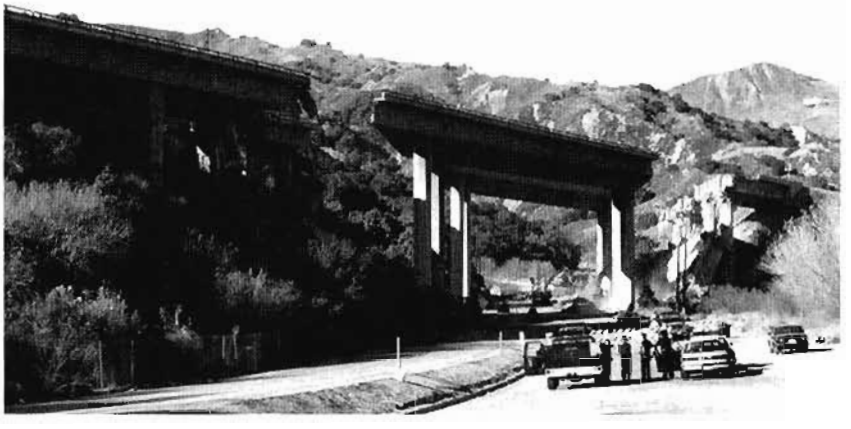

Figure 3-11. *The highly skewed geometry and short expansion joint seat width of the still-standing center frame of the I-5 Gavin Canyon bridge.* (photo: F Seible)

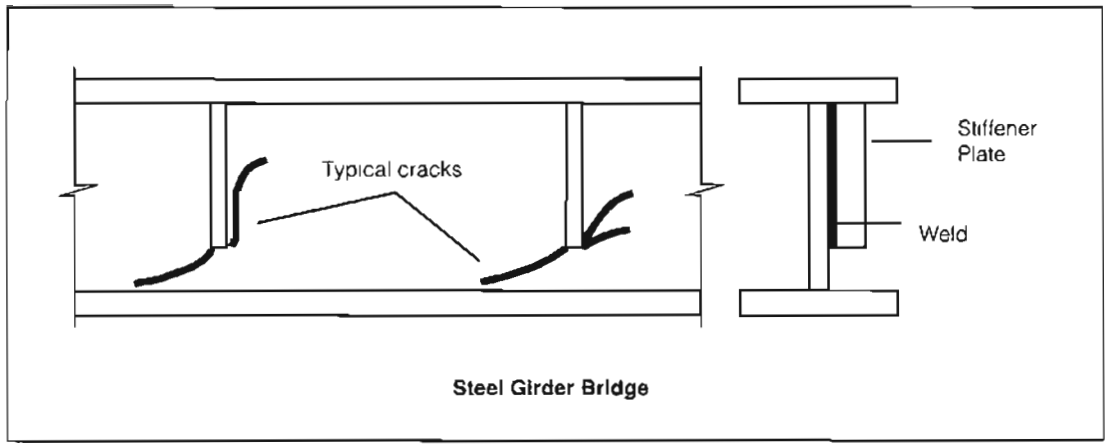

Figure 3-12. *Typical cracking associated with x-bracing observed in some steel girder bridges, Northridge earthquake.*

Similarity of Northridge Earthquake to Loma Prieta and San Fernando Earthquakes

Immediately after each damaging California earthquake since 1971 Caltrans has sent Post-Earthquake Investigation Teams (PEQIT) to survey, investigate, and document the damage and collapse of all Caltrans structures in the affected areas. A detailed documentation of bridge damage can be found in the PEQIT report published after each of these earthquakes, as well as many other publications.

There is great similarity in the types of damage produced by this earthquake and those seen following the 1971 San Fernando and the 1989 Loma Prieta earthquakes. Bridges that were damaged in all three of these events were similar in age and technical characteristics of design. An examination of the PEQIT reports highlights these similarities.

The design profession has known for some time of the deficiencies of the older bridges that have been damaged in earthquakes since 1971. Indeed, the current Caltrans retrofit program is directed at fixing all of these deficient types of structures.The specifics of bridge response in the San Fernando and Loma Prieta earthquakes are discussed in Appendices C and D for comparison.

Performance of New and Retrofitted Bridges in the Northridge Earthquake

No significant damage has been reported to bridges constructed or retrofitted since the 1987 retrofit program began. Two bridges on State Highway 118 (Mission-Gothic and Bull Creek Canyon) that suffered partial collapse during the Northridge earthquake were designed in 1973, but with criteria that did not reflect current performance criteria. These bridges were on the thrust block over the fault slip and were subjected to very strong ground motion.

Most of the remaining bridges that experienced total or partial collapse, as well as other bridges with major damage, were constructed before 1971 and had not been retrofitted. Several of the bridges that suffered major damage (i.e., State Route 14/ I-5 Interchange) had been previously damaged but were completed with essentially the same design and using the original piers and footings; only one replacement pier and one new pier were designed and constructed with spiral reinforcement.

Loss of support at superstructure hinges was a prevalent cause of distress in the 1971 earthquake. The hinge restrainers and seat extenders installed after that earthquake apparently functioned satisfactorily during the Northridge earthquake. Although damage to hinge restrainers, diaphragm anchorages, or bearing seats occurred at 46 separate locations, partial superstructure collapse due to failure of the restrainers occurred only on Route I-5 over Gavin Canyon, where the highly skewed joints and ineffective placement of the restrainers contributed to the loss of support and partial collapse.

The above observations, as well as detailed performance assessments (Priestley, Seible and Uang, 1994) indicate that collapse and major damage to bridges by this earthquake could have been precluded if the bridges had been built or retrofitted to current Caltrans criteria.

Figure 3-13. *Cracks in bottom region of plate girder web, northern bridge of Pico-Lyons Overcrossing* (photo: A. Astaneh-Asl)

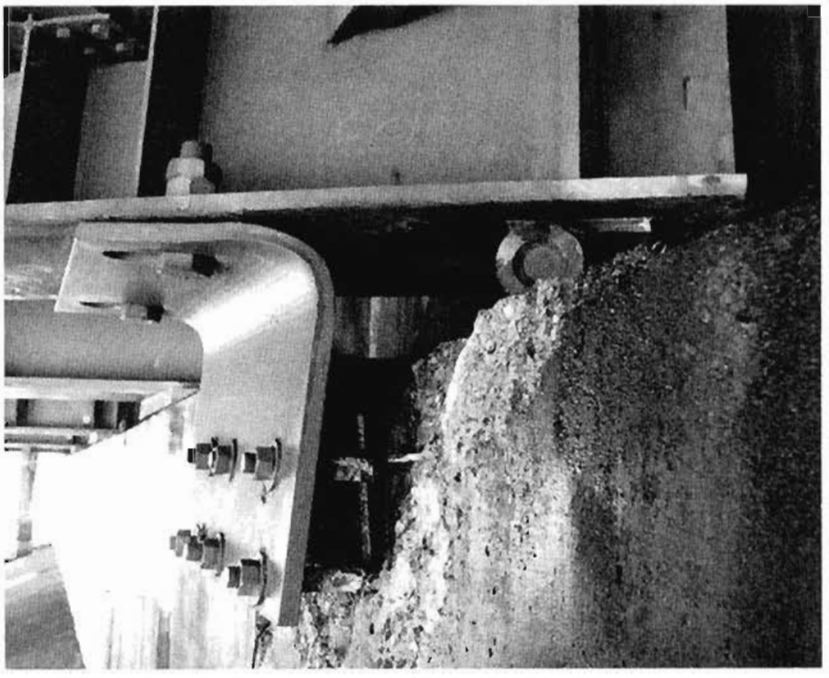

Figure 3-14. *Roller and seismic restrainer damage, southern bridge of Pico-Lyons Overcrossing* (photo: A. Astaneh-Asl)

Figure 3-15. *Support damage at top of Pier No. 6, Santa Clara River Bridge.* (photo: A. Astaneh-Asl)

Performance of Steel Structures

Caltrans has several hundred steel girder bridges in the State Highway System. Approximately 125 steel girder bridges are located in the Greater Los Angeles area and some of these were in the strongly shaken region during the Northridge earthquake. These bridges had all been designed prior to the San Fernando earthquake and as a consequence of the intense ground shaking that they experienced, some sustained significant damage to the end bearings and to the structure supporting the bearings. None of the damaged bridges collapsed but some were in a potentially hazardous condition at the end of the earthquake. It is clear that the weaknesses were a consequence of underestimating the magnitude of the seismic forces that could be developed during an earthquake.

In addition to the damage to the bearings and the supports, several steel girder bridges sustained a different kind of damage to the web-plate of a girder near stiffeners (Figure 3-12). Two skew bridges in the region of very strong shaking have been identified as having such cracks. It appears that some cracks were initiated during the earthquake, and others were there before the earthquake but were extended during the shaking. The worst cracking has already been repaired by grinding out the cracks and rewelding. Damage to the steel girder bridges is illustrated in Figures 3-13 through 3-15 and described in a report to Caltrans prepared by A. Astaneh-Asl and others (Astaneh, 1994).

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Section 4

Why Did Highway Bridges Collapse in the Northridge Earthquake?

Seven highway bridge structures collapsed during the Northridge earthquake (see Table 3-1 in Section 3 for locations). These seven can be classified by vintage into three groups:

1. Bridges designed and built before the 1971 San Fernando earthquake (Gavin Canyon Undercrossing on I-5, the Fairfax & Washington Undercrossing on I-10, and the La Cienega and Venice Undercrossing on the I-10 Santa Monica Freeway).
2. Bridges designed before 1971 but construction completed after 1971 (I-5/SR-14 Antelope Valley Interchange).
3. Bridges designed and built after 1971, but before basic design concepts were changed in 1974 (SR-118 Simi Valley-San Fernando Freeway at Mission & Gothic and Bull Creek Canyon).

This section presents preliminary findings on why these bridges performed as they did. Later research and evaluation efforts should examine bridges that did not fail, so that the differences in performance can be understood and their implications for design codified.

Bridges Designed and Built Before the 1971 San Fernando Earthquake

About 75% of the California's highway bridges were built before 1973, the date when modern seismic bridge design practices were introduced that incorporated the lessons of bridge performance in the San Fernando earthquake. Of the 12,176 state bridges, 9,206, or 76%, were designed before 1973.

Three bridge structures that were completed before, and survived, the 1971 San Fernando earthquake were the Gavin Canyon Undercrossing and the Fairfax & Washington Undercrossing, and the La Cienega & Venice Undercrossing on the I-10 Santa Monica Freeway. In the 1960s, when these bridge structures were designed and built, earthquake engineering in general was not very advanced. This is reflected in seismic bridge design guidelines of that period that required elastic lateral load designs typically for only 6 percent of gravity, without any provisions or considerations for inelastic structural response and ductile design detailing. Key characteristics inherent in these pre-1971 bridge structures are

1. Low transverse reinforcement ratios in columns , typically #4 @ 12" (1/2" diameter reinforcing bars at 12-inch centers) were provided nominally, without consideration of column size or strength.
2. Short seat width at abutments and superstructure expansion joints due to underestimated displacement demands, as a result of the low lateral design loads.

The collapse at the I-5 Gavin Canyon Undercrossing (Figure 4-1) can be attributed to geometric complexities arising from the 66 degree skew orientation of abutments and in-span expansion joints, as well as the 8-inch seat width. Even though retrofitted with first generation restrainers in 1974 (as a direct result of the 1971 San Fernando earthquake), restrainer design and detailing were not sufficient to prevent unseating and subsequent superstructure failure in the acute corners of the bridge at the in-span expansion joints.

Figure 4-1. *I-5, Gavin Canyon Undercrossing, Northridge earthquake.* (photo: F. Seible)

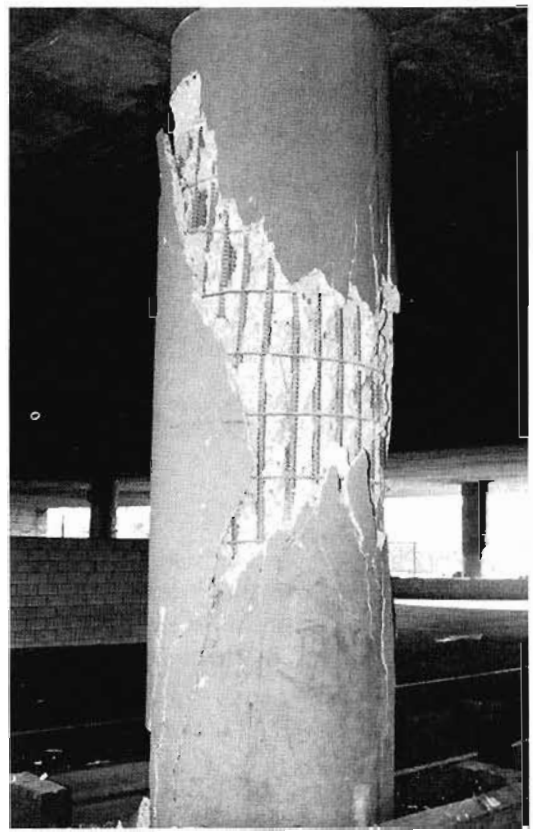

Figure 4-2. *Shear distress pattern at I-10, Fairfax & Washington, Northridge earthquake.* (photo: F. Seible)

Since the restrainer retrofit in 1974, continued research and development of restrainer units funded by Caltrans [Selna, Malvar, and Zelinski, 1989], as well as a better understanding of the skew geometry problems under seismic loads [Priestley, Seible and Chai, 1992], would result now in significantly larger seat width extensions and restrainer capacities. However, quantitative failure assessments immediately following the Northridge earthquake [Priestley, Seible and Uang, 1994] also indicate that shear failure in the shorter bents at the Gavin Canyon Undercrossing was imminent, had unseating and superstructure failure not occurred.

Pre-1971 transverse reinforcement detailing in columns was also a problem due to the low transverse reinforcement (nominal #4 @ 12") for the two bridge collapses at the I-10 Santa Monica Freeway. As stated above, the state-of-the-art in bridge design at the time provided transverse column reinforcement only nominally, and not as a result of engineered capacity requirements that would today result in transverse reinforcement ratios exceeding the nominally-provided ones by a factor of 8 to 10 or more. As a consequence of the low transverse reinforcement and underestimated flexural over-strength, the I-10 structures at Fairfax & Washington (Figure 4-2), and at La Cienega and Venice (Figure 4-3), collapsed with column shear failures either before or shortly after their initial flexural yielding. Quantitative failure assessments of these structures [Priestley, Seible and Uang, 1994] showed that the failure modes encountered could have been prevented with available column retrofit jacketing technology.

Retrofit designs for both of the collapsed I-10 structures were complete at the time of the Northridge earthquake. However, retrofit implementation reportedly was compounded by legal problems concerning the leased airspace under the La Cienega and Venice structures, reemphasizing the fact that time is of essence in the seismic retrofit program.

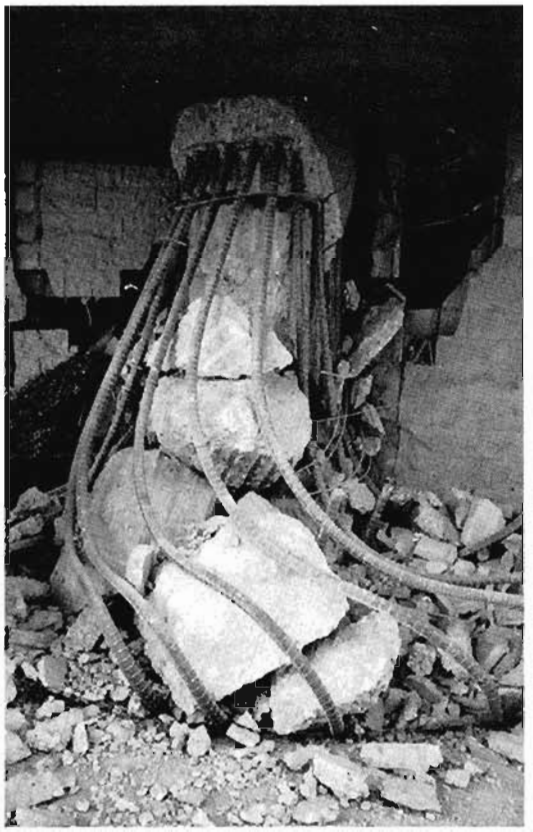

Figure 4-3. *Brittle column failure at I-10, La Cienega and Venice, Northridge earthquake.* (photo: F. Seible)

Figure 4-4. *SR-14/I-5 North Connector Overcrossing, Northridge earthquake.* (photo: F. Seible)

Bridges Designed Before 1971 but Construction Completed After 1971

The second group of bridge structures, the I-5/SR-14 Antelope Valley Interchange, were designed to pre-1971 design standards, but were completed in 1974. This suggests that lessons learned from the 1971 San Fernando earthquake should have been implemented in the redesign.

A common misconception following the Northridge earthquake was that the same bridge structures that collapsed during the 1971 San Fernando earthquake collapsed again this time. Pre- and post-earthquake aerial photographs [Jennings, 1971], clearly show that:

1. The 1971 bridge collapse was in a different separation structure, namely the I-5/SR-14 south separation and overhead.
2. During the 1971 San Fernando event, the two bridge sections that collapsed in the Northridge earthquake were under construction (SR-14/I-5 south connector overcrossing spans 1 and 2 had the bottom soffit, webs and cap beams cast), or were almost complete (the SR-14/I-5 North Connector Overcrossing was complete, with the exception of one column and the last two spans at the north end).
3. All columns in the Antelope Valley Interchange, except for the one mentioned above in 2, were completed and featured the nominal pre-1971 #4 @ 12" transverse column reinforcement.

Because unseating at expansion joints in tall bridges with single-column bents was identified as the primary reason for collapse of bridge structures in the 1971 San Fernando earthquake, the decision at the time must have been to complete the interchange with the already built substructures, but with added expansion joint restrainers to tie the superstructure together and prevent unseating at expansion joints.

During the Northridge earthquake, the two bridge failures at the I-5/SR-14 Interchange (Figures 4-4 through 4-6) can be attributed to brittle shear failure of short or stiff columns. These columns, proportionally to their stiffnesses, attracted more seismic force than their more flexible adjacent bents and did not have the necessary deformation capacity due to the pre-1971 transverse reinforcement detailing [Priestley, Seible and Uang, 1994]. In addition, the shear failure of the north connector of bent #2 was aided by

Figure 4-5. *SR-14/I-5 South Connector Overhead, Northridge earthquake.* (photo: F. Seible)

Figure 4-6. *Short column failure SR-14/I-5 South Connector Overhead, Northridge earthquake.* (photo F. Seible)

Figure 4-7. *SR-118 Mission & Gothic Undercrossing, Northridge earthquake.* (photo: F Seible)

Figure 4-8. *Bull Creek Canyon Channel Undercrossing, SR-118, Northridge earthquake.* (photo: T Saido)

an effective shortening of the column by the construction of a truck ramp shoulder strip around the column with compacted aggregate and asphalt/concrete overlay. Thus, both structures at the I-5/SR-14 Interchange collapsed by brittle shear failure in the short columns next to the abutments with subsequent superstructure unseating at the abutment and superstructure flexural failure at the adjacent bent as a direct consequence of the short column collapse.

Bridges Designed and Built After 1971, but Before Basic Design Concepts Were Changed in 1973

Finally, the two bridges that failed on the SR-118 Simi Valley-San Fernando Freeway at Mission & Gothic and Bull Creek Canyon were clearly post-1971 vintage in both design and construction. Both bridge failures during the Northridge earthquake can be attributed to:

1. Significantly increased stiffness due to decrease in length or effective column-shortening by heavy column flares at Mission & Gothic (Figure 4-7), and by a channel wall at Bull Creek Canyon that was built integral with the columns along a bent line (Figure 4-8).
2. Higher shear demands due to flexural over strength; and,
3. Degrading shear capacities under inelastic cyclic loading at high ductility demand.

At the Mission & Gothic Undercrossing, the column flares, extending over half the column height, were moderately reinforced along the flare. These moderately reinforced flares more than doubled the flexural capacity of the column top in the flared column direction. Transverse reinforcement, in the form of a smooth #5 spiral with 3.5" pitch, was provided along the entire circular column core, and flexural plastic hinging was forced to the bottom of the flare. The increased shear demand led to shear failure and vertical column bar buckling in the plastic hinge region (Figure 4-7) at high local curvature ductilities. At Bull Creek Canyon, only the column ends over a distance of one column diameter were confined with tightly spaced spirals, while the column center portion featured again a 12" pitch. In the bents with the integral channel wall (Figure 4-8), the channel wall top was clearly in the region of low transverse reinforcement ratio that provided little or no ductility to the inelastic flexural hinge that formed on top of

the channel wall and failed in shear at low flexural ductilities [Priestley, Seible and Uang, 1994].

Summary

Following the Northridge earthquake there was speculation that blamed the collapse of bridge structures on:

1. Short seat width at expansion joints.
2. High vertical accelerations.

Unseating of the failed bridge sections at the abutments and expansion joints as the primary collapse source would have required significantly larger displacements at the collapsed bents than the available displacement capacities at these bents. Therefore, the bents would have failed before unseating could have occurred. With the exception of Gavin Canyon, the likely failure sequence started with column shear or flexure/shear failures, with unseating as a direct consequence of the shortening or collapse of the adjacent bents.

Vertical ground accelerations measured during the Northridge earthquake were not disproportionately larger than the measured horizontal accelerations, when compared with other earthquakes (Appendix B). All the described bridge failures can be explained by only the probable horizontal accelerations at the respective bridge sites, [Priestley, Seible and Uang, 1994], without contributions by, or interaction with, vertical ground accelerations.

Design. The bridge structures that collapsed in the Northridge earthquake seem to have been designed based on the best available information at the time of the design. Changes during the construction phase of some of these structures (i.e., the I-5/SR-14 bridges) were not feasible–short of complete demolition and reconstruction–since all columns and most superstructures were already completed at the time of the 1971 San Fernando earthquake and the primary cause of collapse of tall single column structures was attributed to unseating and in-span expansion joints. Retrofit of these bridge structures with expansion joint restrainers was implemented immediately following the San Fernando earthquake.

Retrofit Delays. Subsequent upgrading of these first-generation restrainer retrofits and column retrofit implementation was pending adequate funding and a lack of comprehensive seismic design research results until the 1989 Loma Prieta earthquake. The increased funding following Loma Prieta accelerated the retrofit program and retrofit designs were completed for the I-10 structures, but had not yet been implemented at the time of the Northridge earth quake. Legal problems with leased airspace at La Cienega & Venice, under the bridge structures, have been cited as part of the cause of the delay in retrofit implementation.

The I-5/SR-14 structures were scheduled for retrofit evaluation and design, somewhat lower on the Caltrans prioritization list, due to the post-1971 construction completion date (see Section 5, "Caltrans Bridge Design and Retrofit Program," subsection Retrofit Screening Criteria). The retrofit design was also delayed by the classification of the I-5/SR-14 Interchange in an Alquist-Priolo Special Study Zone and appropriate studies on possible faulting and maximum expected vertical and horizontal offsets had been initiated but not yet completed.

Retrofit Screening Criteria. The SR-118 bridges were originally on the assessed risk priority list, but were subsequently removed due to various criteria such as no internal expansion joints, post-1971 design and construction, and redundancy in the multi-column bents. The reduced effective length of bridge columns through flares, channels or barrier walls, and ground surface modifications are apparently not routinely checked as part of the Caltrans structural vulnerability assessment.

These structural vulnerabilities of effective column shortening, the effects of heavy uni-directional skew geometry, and a better assessment of flexural over strength and actual shear capacities, are known problem areas and need to be incorporated into the routine vulnerability assessment of bridge structures as quickly as possible.

Retrofit Would Have Prevented Collapse. A quantitative assessment of how effective state-of-the-art bridge retrofit technology [Priestley, Seible and Uang, 1994] developed for and by Caltrans over the past eight years shows that all seven of the Northridge earthquake bridge collapses could have been prevented with current seismic retrofit technology. Thus, the critical elements were not a lack of technical understanding or design errors, but rather oversights in the structural vulnerability assessment and, most importantly, the retrofit implementation time factor.

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Section 5

Caltrans Bridge Design and Retrofit Program

Evolution of Caltrans Bridge Design Practices

The damage to bridges in the Northridge earthquake had similarities to that observed in previous earthquakes, particularly the 1971 San Fernando and the 1989 Loma Prieta earthquakes. Each of these earthquakes caused major damage and the collapse of several buildings, bridges, and other structures. Each event has had and will continue to have a major effect on the improvement of the seismic design and retrofit procedures for Caltrans bridges in California.

In 1943, the California State Division of Highways introduced a specific static seismic lateral load requirement into its design specifications for the first time. Bridge design, at that time, considered an equivalent lateral seismic load as a percentage of the dead weight. The percentage varied from 2 to 6 depending upon the soil conditions. Two percent, four percent, and six percent were specified for bridges founded on rock, on soils having 4 tons/ft.^{2} bearing capacity, and on piles, respectively.

In 1963, the Division's Bridge Department adopted the Structural Engineers Association of California (SEAOC) code formulation requiring that the equivalent lateral seismic load (EQ) be determined using the formula EQ = KCD in which D is the dead load of the structure, C is a seismic base-shear coefficient given by $0.05/T^{1/3}$ (T being the fundamental period of the structure) with 0.10 specified as an upper limit, and K is a coefficient representing energy absorption capacity of the structure. A K-value of 1.33 was specified for bridges having wall supports with height-to-length ratios of 2.5 or less, 1.00 was specified for bridges having single-column or pier supports with height-to-length ratios greater than 2.5, and 0.67 was specified for bridges supported on continuous frames. The design provision also specified that the product KC should never be less than 0.02.

In hindsight, and as was demonstrated by the San Fernando earthquake, using building design provisions for bridges was not appropriate. Bridges and buildings share some characteristics, but differ in fundamental ways that make their behavior very different. The building provisions expressed the profession's evaluation of the totality of a building's characteristics and their expectation of its performance in an earthquake. The provisions should only have been used for structures that are similar to buildings, which bridges are not.

The damages to bridge structures during the San Fernando earthquake made it very clear that the above 1963 code provision was inadequate. Thus, the California State Division of Highways immediately instituted changes to increase the 1963 code force level by the factor of 2 for all bridges supported on spread footings and by the factor 2.5 for those bridges supported on pile foundations. Besides increasing the code force level, many structural details were improved considerably. These changes applied only to new designs. Caltrans knew that many of the deficient bridge structures in use were designed using the pre-1971 design criteria, and, consequently, initiated a seismic retrofit program.

A brief chronological summary of some of the major developments in these criteria is given below:

1971-1986: Research results from the 1971 San Fernando earthquake, as well as recommendations developed by the ATC-6 project caused Caltrans to implement new bridge design criteria. During this period, ARS (acceleration response spectrum) ground motion curves and response reduction factors were adopted, which, in general, led to higher design force levels and the specification of robust spiral ties for columns was implemented.

1986-1989: A retrofit program developed by Caltrans identified single-column bridge bents as being potentially the most vulnerable to earthquake damage. Research sponsored by Caltrans at the University of California, San Diego, led to a retrofit procedure that uses steel jackets to increase flexural ductility and shear capacities. Immediate implementation was begun for these bent types.

Post-1989: Following the 1989 Loma Prieta earthquake, Caltrans sponsored accelerated retrofit research primarily conducted at the University of California at Berkeley (UCB) and University of California at San Diego (UCSD) and appointed a Seismic Advisory Board. Peer review panels were selected for the retrofit or replacement of the damaged San Francisco viaducts. The Applied Technology Council project (ATC-32) was initiated to review and revise bridge design criteria. While the draft results of this project are available and have been partially adopted by Caltrans, the project has yet to be completed. Administrative issues have held up the contract for the final period.

Although Caltrans design criteria have not been formally revised, ad hoc criteria and design memoranda have been developed and implemented for replacement, as well as retrofit, of existing bridges. These revised or supplementary criteria include guidelines for development of site-specific ground motion estimates, capacity design to preclude brittle failure modes, rational procedures for joint shear design, and the definition of limit states for various performance objectives.

Hinge restrainers had been installed in a total of about 1,200 bridges in Los Angeles County since the 1971 San Fernando earthquake. At the time of the Northridge earthquake, Caltrans had identified 716 high-risk bridges for retrofit in Los Angeles County—retrofit had been completed for 115 of these bridges, consisting chiefly of steel jackets and footing strengthening at single-column bents.

In 1990, a total of 700 city and county bridges were targeted for retrofit. Only a small number of these were complete at the time of the earthquake, due to funding limitations.

Governor's Board of Inquiry Investigation

A post-Loma Prieta earthquake review was conducted by a Board of Inquiry appointed by Governor George Deukmejian on October 26, 1989. After extensive hearings and studies, the Board submitted its findings and recommendations to the Governor in a comprehensive report, *Competing Against Time*, May 31, 1990. This report gave specific recommendations for action by the Governor, the Director of the Department of Transportation, and transportation agencies and districts. On June 2, 1990, Governor Deukmejian issued Executive Order D-86-90

to implement the Board of Inquiry's recommendations, which contained the following items of importance to Caltrans programs.

1. It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings.
2. The Director of the Department of Transportation shall prepare a detailed action plan to ensure that all transportation structures maintained by the State are safe from collapse in the event of an earthquake and that vital transportation links are designed to maintain their function following an earthquake. The plan should include a priority listing of transportation structures which will be scheduled for seismic retrofit. The Director shall transmit this action plan to the Governor by August 31, 1990.
3. The Director of the Department of Transportation shall establish a formal process whereby the Department seeks and obtains the advise of external experts in establishing seismic safety policies, standards, and technical practices; and for seismic safety reviews of plans for construction or retrofit of complex structures. The Director shall transmit a summary of this process to the Governor by August 31, 1990.
4. The Director of the Department of Transportation shall assign a high priority to development of a program of basic and problem-focused research on earthquake engineering issues, to include comprehensive earthquake vulnerability evaluations of important transportation structures and a program for placing seismic activity monitoring instruments on transportation structures. The Director shall transmit a description of the research program to the Governor by August 31, 1990.

Caltrans Response to Board of Inquiry Recommendations

Caltrans has made fundamental changes in its operations in response to the Board of Inquiry recommendations, and has taken actions to fulfill these requirements on a priority basis.

Caltrans, and in particular the Division of Structures under James Roberts, has responded positively and quickly to these recommendations. They have issued annual status reports on "Caltrans Response to Governor's Board of Inquiry Recommendations and Executive Order of June 2, 1990." (See Appendix A for an abstract of the latest status report, January 26, 1994.)

Caltrans in response to the recommendations has:

1. Appointed a Seismic Advisory Board to review its programs and advise on technical and administrative programs, bringing oversight and contributions from an extended community of earthquake engineering specialists. It has met approximately quarterly since then to review and advise Caltrans on proposals, progress, and implementation actions to meeting the recommendations.
2. Developed an action plan to assure seismic safety of state-owned bridges.

3. Performed vulnerability assessments of the 24,000 state, county, and city bridges and a developed prioritized list to implement a seismic retrofit program.
4. Developed a bridge seismic performance policy.
5. Implemented independent technical peer review of the seismic aspects of important projects, thus opening their design process to influence by a broader technical community.
6. Developed a priority list for the retrofitting of high hazard structures based on a rational procedure.
7. Initiated seismic retrofit design and construction for approximately 2,000 high-hazard structures to be completed over a 10-year period (1989-1999).
8. Instituted changes to the Caltrans Bridge Seismic Design Specifications and Criteria.
9. Established an Office of Earthquake Engineering and conducted extensive training in seismic design for over 200 bridge engineers.
10. Increased commitment to research funding with an initial investment of $8 million, followed by annual expenditures of $5 million on problem-focused seismic research topics.

The above actions are in various stages of progress and will require a continuing management commitment to their completion. The Seismic Advisory Board evaluates Caltrans performance as consistent with the directions of the Executive Order and legislative directions on seismic safety. Appendix A provides a detailed review of the actions, through January 24, 1994, by the Department of Transportation in response to these recommendations and directions.

Peer Review

In response to the Board of Inquiry report, Caltrans implemented a seismic safety peer review process for selected important new or retrofit bridge design projects following the Loma Prieta earthquake. The peer reviews to date have had several different forms and functions, including:

1. Review of seismic design criteria only.
2. Review of criteria and designs.
3. Review of completed designs only.

Both Caltrans and outside engineering consultants have taken the review process very seriously, resulting not only in structural seismic safety improvements, but also in a learning experience for all parties involved.

The Seismic Advisory Board recommends that the peer review process be standardized to make it more effective. The scope of review process should be standardized in terms of:

1. Which bridges are to be scrutinized.
2. Scheduling the review to allow designers and reviewers the time necessary to scrutinize and/or improve on the seismic performance of the bridge structure.
3. Completeness of the peer review, starting with the initial concept and strategy of design and type of selection and continuing through the final seismic design detailing.

The specific terms of content or format should not be standardized; they must be project-specific.

Peer review is currently only implemented for a few special structures (see Appendix A). Yet, as the Northridge experience shows, the seismic performance of

common structures affects the functionality of the transportation system as a whole. The Board believes that peer review also should be implemented for some selected common bridges. This will help ensure that all new and retrofit designs benefit from the best technical knowledge and experience, not just the "important" structures. What makes a bridge "important" needs review and clarification in light of the regional transportation system so that it will be clearer to the public and better defined for engineering design purposes.

As a very positive note, it should be stated that experiences with the peer review process to date indicate that peer review seems to be the vehicle that integrates the latest seismological, geological, geotechnical and structural findings into Caltrans seismic design for bridges and bridge retrofits.

Peer Review and Construction of the Northridge Earthquake Replacement Bridges

Caltrans set a very fast schedule for the removal of all collapsed and unsafe bridges, the replacement of nine bridge structures, and the retrofit of one bridge—all to be completed by December 1, 1994. This schedule provided new challenges not only for demolition and construction, but also for design and seismic safety review. Demolition and construction contracts were given on an invited, prequalified limited bid basis with heavy incentive and penalty clauses for early or late completion, respectively. For this reconstruction effort design submittals are staged to just stay ahead of the construction, and the seismic safety review is based on evolving and continuously changing design concepts and documents.

Nevertheless, Caltrans is implementing significant changes from past design practice based on lessons learned from the Northridge earthquake in terms of:

1. Elimination of most in-span expansion joints through longer jointless superstructures or special hinge bents.
2. Elimination of excessively skewed joints and abutments.
3. Balancing the stiffness of bridge columns within individual frames.
4. Design alternatives in steel and concrete for selected structures.
5. Use of site-specific geological and seismological data for ARS curves and substructure stiffness.
6. Consideration of potential vertical excitations for the superstructure.

All these new concepts, and the associated changes and deviations from established design procedures, were implemented and accomplished in this short period. This indicates a commendable flexibility and capability of Caltrans designers and engineering consultants. The Board believes that the public can have confidence in the seismic safety of these replacement structures.

Table 5-1. *Weights used in the prioritization process. The priority is determined from the formula below where A_f is the fault activity (0.25-1.0), H_f is the sum of the hazard characteristic values, V_f is for vulnerability and I_f for impact. Specific characteristic values range from zero to the maximum value given based on the characteristics of an individual bridge.*
Priority rating index = $(A_f H_f)(0.60 I_f + 0.40 V_f)$

Category/characteristic	Characteristic Weight
Hazard (H_f)	
Soil conditions	33%
Peak rock acceleration	38%
Duration	29%
Vulnerability (V_f)	
Year designed	25%
Outriggers or shared columns	22%
Abutment type	8%
Skewness	12%
Drop type failure	16.5%
Bent redundancy	16.5%
Impact (I_f)	
ADT on structure	28%
Leased air space (residential, office)	15%
Leased air space (parking, storage facility)	7%
ADT under/over structure	12%
Facility crossed	7%
Route type on bridge	7%
Detour length	14%
Critical utility	10%

Caltrans Retrofit and Design Response to Loma Prieta Earthquake

Within weeks after the Loma Prieta earthquake, Caltrans embarked on a massive program to replace, remove or retrofit damaged freeways in the Bay Area. To expedite the process, Caltrans retained outside consultants to design and detail the retrofits of major freeways. Directions to the consultant were issued in the form of memos.

As required by Executive Order D-86-90 from the Governor, Caltrans appointed Peer Review Panels consisting of private practitioners, academicians and researchers to evaluate the work of the Caltrans and its consultants. The peer review panels held regular meetings to review both retrofit criteria and methods, resulting in substantial changes in the work underway. In the case of the San Francisco Double Deck Freeway retrofit program, a number of major issues surfaced. Poor soil conditions led to the need for site specific analyses because existing ARS curves were not felt to be appropriate. Major deficiencies of the original structures were in the areas of insufficient joint shear reinforcing; inadequate reinforcing steel anchorage and laps; large torsion resulting from freeway configuration; and the absence of longitudinal frame action. Rather than an incremental retrofit program, where the first step would permit the opening of the freeways to traffic and the second step would refine the retrofit to provide for post earthquake operational capacity after a future major earthquake, it was decided to combine this work into a single effort.

Table 5-2. *Status of the retrofit review of State highway bridges.*

Stage	Number
Total bridges on the state highway system	11,895
Total screened out in first screening (priority index) stage	4,612
Total screened out in second screening stage (plan review)	3,595
Total screened out in third screening stage (detailed dynamic analysis)	1,151
Total remaining in the retrofit program; some will be dropped as the detailed analysis continues	2,537

Prioritization and Screening Practices

Caltrans experience with retrofit of the damaged bridges in the San Francisco Bay area following the Loma Prieta earthquake in 1989 emphasized the need for a "structural systems" approach to the retrofit of older, seismically deficient bridges instead of a "structural elements" approach. With the support of the Seismic Advisory Board, Caltrans initiated a comprehensive retrofit program.

The decision on whether a bridge should be considered for retrofitting is based on a four step-process for prioritizing structures for retrofit. At any step in the process, a structure can be assessed as acceptable and not further considered.

Table 5-3. *The Caltrans bridge retrofit program status as of June 1, 1994. The proportions are based on the total number of structures affected. M is an abbreviation for millions.* (Caltrans 1994)

Category of structure	Estimated total cost	Construction complete	Construction underway	Remaining
1. Single column retrofit	$120 M	87%	13%	0%
2. Multiple column retrofit	$1,650 M	2%	7%	91%
3. Toll bridge retrofits	$650 M	0%	0%	100%

Screening procedures for retrofitting structures are developed in four steps:

1. A computerized prioritization algorithm was developed to evaluate the various attributes of each bridge and to assign a quantified ranking for retrofit. It employs three major categories for evaluation: 1) vulnerability of structures; 2) seismic hazard; and 3) impact on the community. Each of these categories has a number of specific elements (Table 5-1).
2. Initial screening of the approximately 24,000 state, county, and city bridges in California to determine their seismic vulnerability. About 7,000 state bridges and 4,000 county and city bridges were identified as being potentially hazardous.
3. Detailed plan review of all 11,000 potentially hazardous bridges.
4. Detailed seismic evaluation of the remaining bridges in order of priority to identify structural deficiencies for retrofit (see Table 5-2).
5. Design and preparation of the necessary construction documents to implement the retrofit. Unlike prior retrofit programs, this program systematically addresses deficiencies in all the structural components of each bridge.

Initially there were 11,895 state highway bridge structures to be ranked. Of this group, 2,537 were judged to be hazardous, although since not all third-step studies are complete, this number may be reduced. Table 5-2 shows the sequence of reductions in numbers at the three assessment steps of the review, yielding a best estimate at this time of about 2,000 bridges that will need retrofitting. Of these 2,000 high-risk bridges, 716 were in Los Angeles County. Engineering design has been completed for 800 bridges in the State; construction has been completed for 250; approximately 400 are in the process of being retrofitted.

Although most state bridges were screened out of the current retrofit program, this does not mean that they satisfy modern design and construction standards. At a later date, further consideration must be given to the potential for severe damage or collapse.

Current Status of State Highway Bridge Retrofit Program

A total of 2,537 state bridges remain in the current retrofit program based on the screening procedure discussed above. Further screening and preliminary structural evaluation have resulted in identification of about 2,000 state bridges that require detailing evaluation and retrofit. As indicated in Figure 5-2, retrofit plans have been completed for approximately 800 bridges, bids have been opened for 400, and retrofit has been completed on about 250.

The retrofit program for state highway bridges has been divided into three parts—single-column, multiple-column, and toll-bridge programs—with a total estimated cost of $2,420 million (Table 5-3). All projects are in progress with the indicated percentages for structures with construction complete, and under construction. Figure 5-1 graphically illustrates the proportion of structures impacted in each of the nine project categories from *Ready For Assignment* to *Construction Completed*.

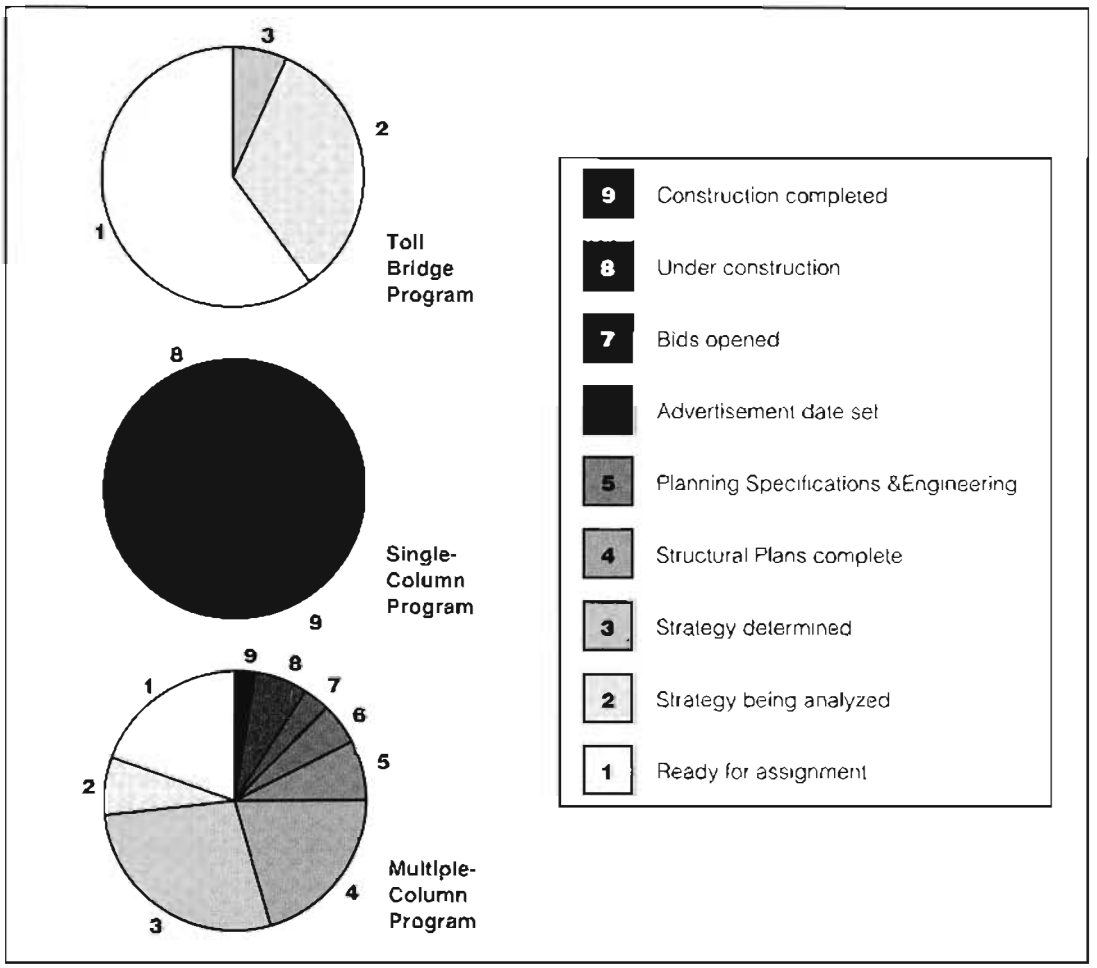

Figure 5-1. *Pie charts show the status of the single-column, multiple-column and bridge retrofit programs for state highway bridges. The segment represents the proportion of the structures in the particular category of completion compared to the number of structures affected*

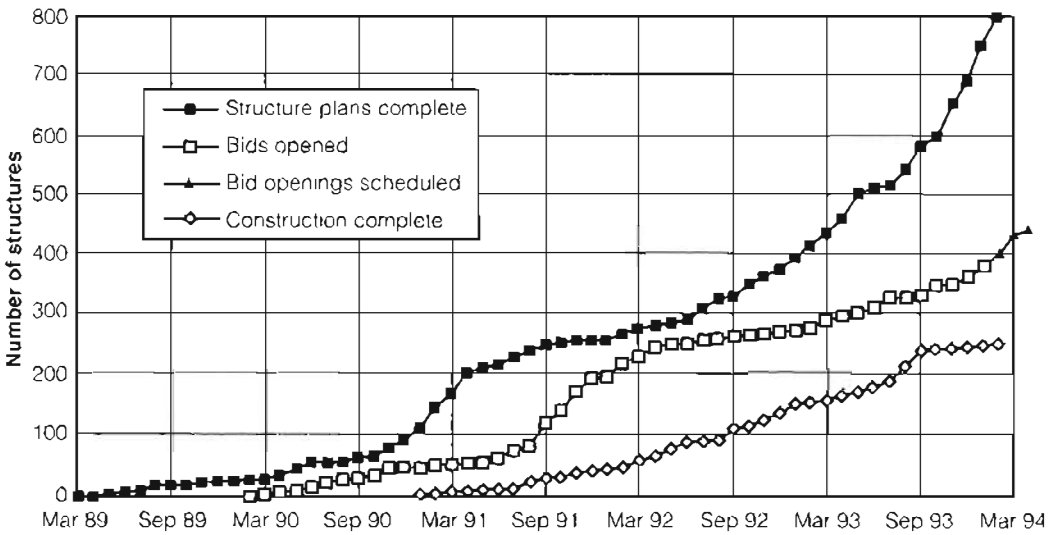

Figure 5-2. *Total numbers of seismic safety retrofit projects for state highway bridges in different stages of completion since March 1989. Note that the program accelerated substantially following the Loma Prieta earthquake on October 17, 1989*

Table 5-4. *Status of toll bridge seismic studies. The dates given are those when the phase of the study was completed or is scheduled to be completed; T indicates target, C indicates completed, and * indicates that the target date is based on Caltrans' ability to contract work with consulting engineering firms.*

	Date of completion or scheduled completion		
Bridge	**Hazard**	**Vulnerability**	**Design PS&E**
San Francisco-Oakland Bay Bridge (12 distinct design projects)[1]			
West spans	C 12/92	T 8/94	T 6/96
East spans	T 5/94	T 5/94	T 6/96
Dumbarton Bridge	C7/93	T 5/94	Unscheduled*
San Mateo-Hayward Bridge	C 2/93	C 11/93	T 6/96*
Richmond-San Rafael Bridge	C 6/93	T 12/94	T 6/96*
Carquinez Bridge	C 2/93	C 12/93	T 6/96*
Benicia-Martinez Bridge	C 12/92	C 8/93	T 6/96*
Antioch Bridge[2]	C 9/93	T 5/94	Unscheduled*
San Diego-Coronado Bridge	T 7/94	C 7/95	T 6/96*
Terminal Island (Vincent Thomas) Bridge	T 7/94	C 11/91	T 6/96*
Commodore Schuyler Heim Bridge[3]	T 12/94	N/A	N/A
Terminal Island (Gerald Desmond) Bridge[4]	T 12/94	N/A	N/A

Notes
1. Some retrofit construction is complete (Pier E-9), having been initiated immediately after the Loma Prieta earthquake; other construction will be initiated in the summer of 1994 and continue until all projects are completed.
2. A recently completed design that may require retrofit work.
3. This bridge is on soft ground over an oil field that has been settling for years. No amount of retrofitting would guarantee continued operation.
4. Bridge built by the Port of Long Beach. It will become part of the state highway system in the near future. Caltrans is negotiating an agreement to have Port bring it up to current maintenance standards before acceptance. Seismic vulnerability studies will be initiated upon acceptance.

Figure 5-2 graphically emphasizes the remaining vulnerability of the state highway system. In particular, it should be noted that retrofit plans have not yet been completed for any of the 11 toll bridges in California. Most of these bridges, such as the San Francisco Bay Bridge, are vital to the economic welfare of the area.

None of the toll bridge retrofit projects are yet in construction. Toll bridges are very complex structures, requiring substantially more effort than do conventional bridges. The seismic retrofit program for these structures has been approached in three parts:

1. Hazard analysis
2. Vulnerability analysis
3. Design planning, specifications and engineering (PS&E)

Table 5-4 gives the status of these studies for each of the 11 toll bridges for which Caltrans is responsible. Hazard analyses have been completed for all the toll bridges, with the results having been made available for vulnerability assessments. Vulnerability analyses are complete for some of these bridges and retrofit designs are underway.

While the rate of preparation of retrofit plans, as indicated in Figure 5-2, appears to be accelerating, the debilitating effect of the lawsuit by the PEG group (Caltrans employees) is evidenced by the flat portion of the curve in May-July of 1993. Additionally, it appears that there is a rapidly increasing gap between the number of retrofit plans that are completed and the number of contracts that are advertised and awarded.

Table 5-5. *Status of the seismic retrofit of city and county bridges throughout the State. Note that the classifications are somewhat different than those used for state highway bridges in Table 5-2.*

Stage	Number
Total bridges on the highway system	12,000
Total screened out in first screening (priority index) stage	6,807
Total screened out in second screening stage (plan review)	4,152
Total remaining in the retrofit program after second screening stage	1041
Total left to be assessed in third screening stage (detailed analysis)	648

Current Status of City and County Bridge Retrofit Program

Table 5-5 indicates the status of the retrofit program for county and city bridges undertaken by Caltrans as directed by law, even though the bridges themselves are under local jurisdiction. Of the 12,000 total bridges in these systems only 1,041 (8.7%) remained after the second screening compared to 31% for the state bridges. State bridges tend to be larger than local government bridges and thus tend to be more vulnerable and have larger impact in case of failure or closure. Construction is complete for 18 and underway for another 36; 165 remain to have the retrofit design process initiated, and 648 have yet to have had their third level investigation.

Summary

In summary, the 1971 San Fernando and the 1989 Loma Prieta earthquakes both had a major impact on increasing the awareness of the seismic risks to bridge structures in California. Following the Loma Prieta earthquake, Caltrans responded positively to the recommendations of the Governor's Board of Inquiry for improving the seismic safety of highway bridges outlined in *Competing Against Time*.

All post-Loma Prieta retrofitted bridges performed well in the Northridge earthquake. All of the bridges in the region of strong motion are in the "common" class. Of the seven bridges that collapsed, five had been identified and scheduled for seismic retrofit. Two, the Mission & Gothic Undercrossing and Bull Creek Canyon Channel Undercrossing on State Route 118, had been evaluated as not currently requiring retrofit . In light of this experience, it is advisable to review the prioritizing procedure and reexamine the retrofit decision for those bridges that were eliminated from the retrofit program to determine if they should be reconsidered. The seismic safety of common other bridges should also be examined for possible retrofit.

It is essential that retrofit of the remaining deficient bridge structures in California be accelerated so that, hopefully, it will be completed before the next major earthquake occurs. Whatever actions and support are required to accomplish this must be provided by the Governor and the State Legislature.

Section 6

Improving the Caltrans Seismic Program

Retrofit Prioritization Procedures

The Northridge earthquake has shown that the ambitious retrofit prioritization program undertaken by Caltrans for all of the State's 24,000 bridges has been effective. However, it is not flawless and needs continued scrutiny and updating. This section presents some of the Seismic Advisory Board's suggestions for improvement based on observations of system performance in the Northridge earthquake and reconsideration of some past decisions Caltrans has made.

It can be argued that the uncertainties in assessing seismic hazard and the complexities of determining structural vulnerability cannot be quantified into a deterministic, numerical risk assessment and retrofit prioritization. Caltrans is well aware of this argument. The Caltrans risk assessment algorithm, which has been continuously modified and updated over the past three years, is only used as a *prescreening* tool. All the bridge structures that collapsed in the Northridge earthquake were initially identified as potential retrofit candidates using this algorithm. However, two of these were removed from the list on the third step of screening.

The subsequent manual screening of all identified candidate structures relies heavily on subjective judgments by individual review engineers and, consequently, is prone to human error and omissions. Again, Caltrans tries to minimize these problems by having at least two independent reviews, with arbitration in case of differences. The fact that only two bridges of 506 bridges located within the strong shaking area (PGA≥0.5g) were misjudged by the Caltrans risk assessment procedure is actually quite remarkable.

After a preliminary assessment of observations from the Northridge earthquake, the Seismic Advisory Board suggests the following actions be taken by Caltrans:

1. Review of Phase I expansion joint retrofits in terms of restrainer orientation, restrainer capacity, detailing and seat width extension, and vulnerability of columns.
2. Train review engineers to look for effective length of columns as modified by flares, walls, or ground surface conditions.
3. Train review engineers to assess potential ductile vs. brittle failure modes in columns.
4. Rescreen all bridge structures based on the latest hazard and vulnerability findings.

These actions should be incorporated as expediently as possible into the retrofit prioritization procedure and training programs.

While almost all bridge design is based on linear elastic methods, damage is caused by nonlinear response. Linear elastic design methods are formulated so that they provide adequate nonlinear response in most cases. While linear approaches may be quite serviceable in most cases, some applications require non linear analysis to properly understand the structures response and judge the adequacy of a design. Nonlinear analysis can be applied both to dynamic time history and static approaches, in the latter case pushover analyses are one commonly used approach. The Board believes it to be important that Caltrans develop the staff capable of performing nonlinear analyses for both complete bridge systems and for

sections of bridges. It further believes that all Caltrans design engineers should be well informed as to the limitations of linear elastic analysis and the circumstances when each is appropriate.

Finally, retrofit designs, and particularly implementations, need to proceed as quickly as possible for all bridge types, without consideration of restrainers first, single-column bents second, multi-column bents third, and toll bridges separately or fourth. The highest risk (including the greatest consequence of failure) is likely to be found independent of the these basic types of categories.

For example, the Board could make an argument for retrofitting all major toll bridges first, since their failure or closure would have severe and extreme economic impacts. A good argument could also be made for doing multi-column bent bridges next, since those columns are prone to shear failure due to their shorter length and the potential for brittle failure mechanisms without ductility or energy absorption to withstand the duration of strong ground shaking. Assigning priorities for retrofit based on categories like these tends to obscure the relevance of a particular bridge's vulnerability compared to others.

The Board believes that the methods used to assign priority needs rethinking. The current system uses one index to determine the priority and it may not be robust enough to order bridges properly. It may be necessary to use more complicated approaches than the current one. Future priority assignment systems must recognize all of the factors and specific characteristics for each bridge that contribute to its hazard, vulnerability, and importance valuations.

Site-Specific Studies

The Northridge earthquake indicates the importance of Caltrans undertaking specific geotechnical studies for all new designs or retrofits of major bridges and for sites that are expected to perform poorly. The evidence of the Northridge earthquake is that motions at several of the collapsed bridges may have been significantly amplified by the local soil conditions. Current weighting factors in the prioritization procedure apply too little weight to the geotechnical conditions of the site and their variations along the length of a structure.

Use of Earthquake Prediction for Priority Setting

The Northridge earthquake could not have been forecast as to specific place, time and size. Though it occurred on a blind-thrust fault, it was not unexpected, because it lies within in a broad region where such active faults are known to occur.

In general, quantitative statements on the probability of future earthquakes are of limited value in deciding Caltrans retrofit priorities. Nevertheless, when the importance factors for structures are considered, there are certain tectonic regions of the State where the likelihood of intense strong motions in the lifetime of the structures can be specified with some confidence. This geological and geotechnical knowledge, where available, should guide the design of new structures and the prioritization for retrofit of structures.

Research Should be Enhanced

Caltrans has made a commitment to support research and development, and has sustained a $5 million per year research program on bridges since the Loma Prieta earthquake. The evidence suggests that it will continue this commitment. There is, however, more to do than this budget commitment allows.

The Northridge earthquake confirmed laboratory test results on the effectiveness of bridge column retrofitting to prevent structural collapse, thereby mitigating damage and decreasing disruption following an earthquake. However, it needs to be emphasized that the last two earthquakes with significant bridge damage—Loma Prieta in 1989 and Northridge in 1994—were of the "moderate" category. The "large" earthquakes, still to occur, will provide more severe testing of design and retrofit practices. Thus, no field evidence is yet available on how retrofitted bridges, as currently designed, will perform under maximum expected ground motions. Research is the only way to develop a full understanding of what bridges and other structures will be subjected to during longer-duration ground motions prior to their occurrence. The "large earthquakes" will probably not produce significantly higher peak ground motions at a point, but will produce these higher motions over much greater area and for a longer time, thus affecting a vastly larger number of structures than were effected in the Northridge earthquake.

The Caltrans retrofit program first added restrainers in expansion joints and, next, retrofitted single-columns with steel jackets. These weak elements in the bridge structure provided a structural fuse whose failure protected other elements of the structure that also may be very damage-prone. Now that these retrofitted elements can be expected to survive, adjacent structural elements, such as footings, superstructure/column connections and, in particular, abutments, will be subjected to previously unreached force levels and deformation demands. Thus, significant damage in these adjacent bridge members can be expected in future seismic events.

It is essential that the Caltrans comprehensive seismic bridge retrofit research program be continued and accelerated to address the behavior of bridges as complete, interconnected systems, including soil effects. Research should focus not just on safety or "no collapse" criteria, but also on functionality or serviceability criteria that clearly outline the expected bridge damage, repairability, and bridge or route closure consequences.

The Seismic Advisory Board recommends that the following research and study agenda be addressed:

1. The contributions of site-specific geological, seismological, and geotechnical characteristics.
2. Response of bridges as complete systems using nonlinear as well as linear approaches.
3. Determination of the types and extent of damage to different types of elements that corresponds to the thresholds for different performance levels; for example, what degree of cracking in a reinforced concrete column is acceptable before it is closed for repairs, or must be removed and replaced.

4. Predicting the expected damage states for specific bridge systems using different design approaches and construction details in specified earthquake ground motions, including those used for both functional and safety evaluations.
5. Functionality criteria for post-earthquake repairability and serviceability.
6. A comprehensive strategy whereby research results and other state-of-the-art advances in engineering are incorporated into Caltrans design practice. This implementation program should coordinate research programs and ensure that new knowledge and technology are incorporated into both the structural vulnerability assessment as well as into retrofit implementation and new bridge design in the shortest time frame possible.

The Board also recommends that Caltrans pay special attention to reassessing and upgrading Phase I restrainer retrofit technology, since it is now known that larger forces and displacements can be expected from retrofitted bent systems. This may require replacing some restrainer systems and strengthening some foundations, and verify that columns will not fail in shear.

Finally, the design and evaluation criteria for design of bridge structures needs to be regularly reviewed and revised to reflect the latest seismological, geological, geotechnical, and structural research findings.

The focus of research and professional practice development to date has been on reinforced concrete and older steel bridges. Observed damage to modern steel buildings suggests that there may be serious seismic performance problems associated with current design and construction procedures for steel bridges. These issues need to be investigated with the objective of ensuring that Caltrans bridge designs are not subject to the same types of failure problems.

Appendices

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Appendix A

Caltrans Response to Governor's Board of Inquiry Recommendations and Executive Order of June 2, 1990

January, 1994 Status Report

This Appendix reproduces, with minor deletions, the Department of Transportation's January 1994 report on the status of actions in response to the Governor's Board of Inquiry Recommendations and Executive Order of June 2, 1990, [Caltrans, 1994].

The Seismic Advisory Board finds that the Department of Transportation has responded very positively to: 1) Each of the eleven recommendations the Governor's Board of Inquiry presented in their report *Competing Against Time*, dated May 31, 1990; 2) Governor George Deukmejian's Executive Order D-86-90, dated June 2, 1990; 3) the requirements of Senate Bill 36X, signed into law by Governor Deukmejian on November 6, 1989; 4) to Senate Bill 2104 (Kopp). Each of these four documents recommended and mandated specific aspects of a continuing and aggressive seismic safety program for transportation structures. The following Caltrans detailed report, dated January 26, 1994, addresses each of the eleven items recommended in *Competing Against Time* specifically and includes attachments containing more detail.

Caltrans Report, January 26, 1994

The progress report of the current status of the Department's Bridge Seismic Safety Program is addressed in "Seismic Safety Retrofit Program-Annual Report" to be presented to the California Transportation Commission on February 24, 1994. From a total of 2,500 Single Column supported bridges on the State highway system, 259 have been identified as needing retrofit upgrading after all screening and analysis have been completed. Of these 259 bridges, 258 have been completed or are under construction, and the remaining are being designed and will go to construction within a few months. The remaining 9,500 bridges on the system are multiple column supported structures. Initial screening pared that list down to 4,500 that require dynamic analysis to determine their status, and we estimate that approximately 774 will require retrofitting. In this category, 96 are under construction or completed, plans are completed on 470, and design is underway on 208. The remaining bridges are in various stages of analysis and screening. We have more than 50 consulting firms assisting the Department staff and will complete all plans on these bridges by December 31, 1994. The 8 Toll Bridges are in various stages of analysis and design and will be under construction by the end of 1995.

1 Board of Inquiry Recommendation No. 1 for Action by the Governor.

Affirm the policy that seismic safety shall be a paramount concern in the design and construction of transportation structures. Specific goals of this policy shall be that all transportation structures be seismically safe and that important transportation structures maintain their function after earthquakes.

Governor Deukmejian's Executive Order D-86-90 of June 2, 1990. "It is the policy of the State of California that seismic safety shall be given priority consideration in the allocation of resources for transportation construction projects, and in the design and construction of all state structures, including transportation structures and public buildings" and

"The Director of the Department of Transportation shall prepare a detailed action plan to ensure that all transportation structures maintained by the state are safe from collapse in the event of an earthquake and that vital transportation links are designed to maintain their function following an earthquake. The plan should include a priority listing of transportation structures which will be scheduled for seismic retrofit. The Director shall transmit this action plan to the Governor by August 31, 1990."

Status on January 26, 1994: "Report To The Governor On Seismic Safety, August 31, 1990" was submitted by the Department in response to the Executive Order. The report describes the action plan to assure seismic safety of state-owned bridges. Included is the initial list of 7,000 bridges potentially needing some degree of seismic analysis, evaluation and possible retrofitting. Also described in this report are the makeup of the Seismic Advisory Board, the Seismic Research Advisory Panel, use of Seismic Safety Peer Review Panels and the Seismic Research Program.

By July, 1990, Department Engineering staff had completed an initial "Vulnerability Analysis" of the 23,000 state, county and city bridges and produced a prioritized list from which to complete the seismic safety retrofit program. The logical strategy was to retrofit or replace the most vulnerable bridges on the list first, when this approach is possible. That initial screening list contained approximately 7,000 state and 4,500 city and county bridges which required further analysis and evaluation before a determination could be made as to seismic retrofit needs.

A bridge seismic performance policy was developed in 1991 by the Department of Engineering staff for state-owned bridges and was approved by the Department's Seismic Advisory Board in September, 1992.

2 Board of Inquiry Recommendation No. 4 for Action by the Director of the Department of Transportation. **Prepare a plan, including schedule and resource requirements, to meet the transportation seismic performance policy and goals established by the Governor. The plan shall include the timely seismic retrofitting of existing transportation structures.**

Status on January 26, 1994: "Bridge Seismic Retrofit Program, January 1, 1991." A schedule for project completion and cost estimates was submitted to the Governor on January 1, 1991 in response to his Executive Order D-86-90 and to the Legislature in response to Senate Bill 2104. For the first time an attempt to segregate the 7,000 state-owned bridges into priority groups was included in the report. This was for the purpose of identifying those most critical bridges that needed immediate repair versus those which would only be repaired for purposes of reducing future damage. A form of triage if you think of it that way. It is estimated by Caltrans structural engineers, based on their past experience, that the number of state bridges actually needing any work will be pared down to approximately 4,500.

3 Board of Inquiry Recommendation No. 5 for Action by the Director of the Department of Transportation. **Form a permanent Earthquake Advisory Board of external experts to advise Caltrans on seismic safety policies, standards and technical practices.**

Governor Deukmejian's Executive Order D-86-90 of June 2, 1990. "The Director of the Department of Transportation shall establish a formal process whereby the Department seeks and obtains the advice of external experts in establishing seismic safety policies, standards, and technical practices; and for seismic safety reviews of plans for construction or retrofit of complex structures. The Director shall transmit a summary of this process to the Governor by August 31, 1990."

Status on January 26, 1994: In response to the Governor's Executive Order D-86-90 the Seismic Advisory Board was formed and reported in the "Report To The Governor On Seismic Safety, August 31, 1990." The Department has established a Seismic Advisory Board of eight leading experts in this field. Department Bridge Earthquake Engineering staff and management meet with the Board quarterly to obtain their approval of new criteria and solicit their advice on future developments. Four of the eight Board members were also members of the Governor's Board of Inquiry and one is

the chairman of the Engineering Criteria Review Board for BCDC. Another member is the Chair of the Seismic Research Advisory Panel. To date they have reviewed Caltrans Division of Structures' design procedures, the seismic vulnerability analysis algorithm and screening procedures, the seismic performance criteria, the process utilized by the Seismic Safety Peer Review Panels and many other aspects of our earthquake engineering operations.

4 Board of Inquiry Recommendation No. 6 for Action by the Director of the Department of Transportation. Ensure that Caltrans seismic design policies and construction practices meet the seismic safety policy and goals established by the Governor:

Recommendation A. Review and revise standards, performance criteria, specifications, and practices to ensure that they meet the seismic safety goal established by the Governor and apply them to the design of new structures and rehabilitation of existing transportation structures. These standards, criteria and specifications are to be updated and periodically revised with the assistance of external technical expertise.

Status on January 26, 1994: The Applied Technology Council was awarded a contract in 1990 to review and recommend changes to the Caltrans Bridge Seismic Design Specifications and criteria. That work is nearing completion and the final report with recommendations will be available by the end of 1994. In the interim, many changes have been made to the Seismic Design criteria and procedures as various research work is completed and results/ recommendations can be incorporated into the specifications.

Recommendation B. Institute independent seismic safety reviews for important structures.

Status on January 26, 1994: We have engaged several Seismic Safety Peer Review Panels to review critical and major projects and to comment on our bridge seismic design criteria and details. These Peer Review Panels vary in size depending on the specific project. These panel members have participated in detailed seismic safety design reviews of several major Caltrans projects in all areas of the state.

Projects that have been Peer Reviewed are selected by the Division of Structures based on size, complexity or some unique features and include the following:

1. I-110 Transitway (Harbor Freeway) elevated viaduct in Los Angeles
2. I-480 (Embarcadero Freeway Viaduct) double deck viaduct in San Francisco
3. I-480 (Terminal Separation) Multiple Level Interchange in San Francisco, at the west end of the SFO Bay Bridge-for retrofitting
4. I-280 (China Basin Viaduct) double level viaduct in San Francisco
5. I-280 (Southern Freeway Viaduct) double level viaduct in San Francisco

6. I-280/US101(Alemany Interchange) multiple level interchange in SF
7. US 101 (Central Freeway) double level viaduct in San Francisco
8. I-215/10 Interchange in San Bernardino
9. I-580/I-980/SSR24 Interchange in Oakland
10. I-480 (Terminal Separation) multiple level interchange in San Francisco, at the West end of the SFO Bay Bridge–for replacement structures
11. I-880 replacement project in Oakland
12. San Francisco-Oakland Bay Bridge

Recommendation C. Conduct a vigorous program of professional development in earthquake engineering disciplines at all levels of the organization.

Status on January 26, 1994: The Office of Earthquake Engineering was created in 1990 by combining some smaller units in the Division of Structures. The office is staffed with several engineers with advanced degrees, including 6 with Ph.D.s (a first in Caltrans Structures Division). We have hired a staff Seismologist to augment the existing staff of engineering geologists. We have created a staff seismic design specialists at the Senior Engineer level in each of the 14 Bridge Design sections. We have conducted extensive training in seismic design for over 200 bridge design engineers. We have held numerous workshops between the seismic research community and our designers and consultants to exchange the latest in seismic technology.

A Bridge Seismology Committee was authorized by the Board of Directors of the Structural Engineers Association of California (SEAOC) in July, 1991 and organized shortly after that time. The committee is chaired by James H. Gates, Chief of the Caltrans Office of Earthquake Engineering, and is represented by several Caltrans seismic specialists and structural designers as well as SEAOC members from each of the four local associations. Many of the SEAOC members of this sub-committee are also members of the Peer Review Panels and the ATC Project Engineering Panel, so we have not been working in a void.

Recommendation D. Fund a continuing program of basic and problem-focused research on earthquake engineering issues pertinent to Caltrans responsibilities.

Governor Deukmejian's Executive Order D-86-90 of June 2, 1990. "The Director of the Department of Transportation shall assign a high priority to development of a program of basic and problem-focused research on earthquake engineering issues, to include comprehensive earthquake vulnerability evaluations of important transportation structures and a program for placing seismic activity monitoring instruments on transportation structures. The Director shall transmit a description of the research program to the Governor by August 31, 1990."

Status on January 26, 1994: This program was described in the "Report To The Governor On Seismic Safety, August 31, 1990." The initial investment in bridge seismic research was $8 million and is outlined in the report. Subsequently, the Department management has agreed to a problem-focused seismic research program at an annual expenditure level of $5 million (approximately 1% of the Caltrans bridge capital expenditure program).

5 BOARD OF INQUIRY RECOMMENDATION NO. 7 FOR ACTION BY THE DIRECTOR OF THE DEPARTMENT OF TRANSPORTATION. **Take the following actions for specific structures:**

Recommendation A. Continue to sponsor and utilize the Independent Review Committee's technical reviews of the engineering design and construction proposed for the short-term repair and strengthening of the San Francisco Freeway Viaducts.

Status on January 26, 1994: The Department has continued to utilize the services of the independent Seismic Safety Peer Review Teams for over four years and the work is nearly complete. Most reconstruction is either under contract or scheduled for contract award this calendar year.

Recommendation B. Develop a long-term strategy and program for the seismic strengthening of existing substandard structures, including the San Francisco Freeway Viaducts, that considers their overall behavior, the degree of seismic risk, and the importance of the structure to the transportation system and to the community.

Status on January 26, 1994: This program was described in the report to the Governor "Bridge Seismic Retrofit Program, January 1, 1991." The importance factor is now a part of the Seismic Performance Criteria adopted by the Department and approved by the Seismic Advisory Board. The current status of the seismic retrofit strengthening program is described in the "Bridge Seismic Retrofit Report" dated January 7, 1994.

Recommendation C. Perform comprehensive earthquake vulnerability analyses and evaluation of important transportation structures throughout the state, including bridges, viaducts, and interchanges, using state-of-the-art methods in earthquake engineering.

Status on January 26, 1994: By July, 1990 DOS staff had completed an initial "Vulnerability Analysis" of the 23,000 state, county and city bridges and produced a prioritized list from which to complete the program. The logical strategy was to retrofit or replace the most vulnerable bridges on the list first, when this approach is possible. That list contained approximately 7,000 state and 4,500 city and county bridges which required further analysis and evaluation. To date 1,033 bridges have been identified that require seismic retrofitting.

Recommendation D. Implement a comprehensive program of seismic instrumentation to provide measurement of the excitation and response of transportation structures during earthquakes.

Status on January 26, 1994: The Department increased its annual support of the California Division of Mines and Geology (CDMG) Strong Motion Instrumentation Program (SMIP) from $40,000 to $100,000. Working with the Seismic Advisory Board we have agreed to fund instrumentation for 20 additional bridges at a one time cost of $700,000.

6 Board of Inquiry Recommendation no. 8 for Action by the transportation agencies and districts. **Agencies and independent districts that are responsible for transportation systems, rail systems, highway structures, airports, ports and harbors-should:**

Recommendation A. Adopt the same seismic policy and goals established by the Governor for State transportation structures and implement seismic practices to meet them.

Status on January 26, 1994: It is difficult for Caltrans to determine whether any of these agencies adopted policies and goals or whether they implemented practices to meet them. Caltrans has no authority to require these agencies to comply with the directive.

Recommendation B. Perform comprehensive earthquake vulnerability analysis and evaluation of important transportation structures (e.g., the BART Trans-Bay Tube and Golden Gate Bridge) using state-of-the-art methods in earthquake engineering, and install seismic instrumentation.

Status on January 26, 1994: It is a known fact that the Golden Gate Bridge and Transportation District has conducted a seismic vulnerability analysis of the Bridge and has a consultant preparing seismic retrofit plans for the bridge. Caltrans has no information on seismic instrumentation, however.

Recommendation C. Institute independent seismic safety reviews for important structures.

Status on January 26, 1994: It is known that the Golden Gate Bridge and Transportation District has conducted a seismic safety review of the bridge.

Recommendation D. Conduct a vigorous program of professional development in earthquake engineering disciplines at all levels of their organizations.

Status on January 26, 1994: It is not known to Caltrans whether any of the agencies has conducted such a program.

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Appendix B

Seismological and Strong Motion Description of the January 17, 1994 Northridge Earthquake

Seismological Characteristics

The January 17, 1994 main shock of the Northridge earthquake sequence (M_W=6.7) had a hypocentral location of 34° 13'N, 118° 32'W with a focal depth of about 18 km (see Figure B-1). The hypocentral locations of hundreds of aftershocks have fixed the fault plane as dipping 42° to the south under the San Fernando Valley and striking about 122° (see Figure B-2). The analysis of the wave forms in this earthquake at near and distant stations, together with the measured geodetic displacements, indicates that the rupture mechanism on this fault, called the Northridge fault, was a thrusting mechanism with Granada Hills and the San Fernando Valley on the hanging wall moving northeast.

The area of rupture is inferred to be approximately 16 km along the strike and 15 km in the direction of slip. Slips across the thrust fault had maximum values of about 3.5 m, with an average slip of about 1.5 m over the whole faulted surface. No ground rupture of the thrust fault was observed at the surface and the indication is that the rupture plane lost its structural coherence at a depth of about 5 km on the north and about 20 km on the south; fault displacements above 5 km in depth were perhaps transferred to numerous surficial faults in the Santa Susanah Mountains. Because the faulting did not appear at the surface, the seismic source is termed a "blind-thrust." It thus resembles the Whittier Narrows seismic source that was located under east Los Angeles and ruptured on October 1, 1987, (M_W = 6.0). The seismograms indicate that the release of energy was not uniform along the slip surface; there was at least one secondary release of energy initiated about 3 seconds after the start of the first rupture at the hypocenter.

A number of moderately large aftershocks were produced by additional faulting in the following weeks, the largest on March 20, 1994 having a magnitude of M_W = 5.3, occurring on a subsidiary fault with slip in the upper 5 km of the crust.

An earthquake of this size was not unexpected in the Los Angeles and San Fernando basins where many capable faults of various types are mapped on the State fault map. In addition, it has been clearly demonstrated by the 1987 Whittier Narrows earthquake that substantial earthquakes can be generated by slip on thrust faults that do not have clear expressions at the surface. The network of blind-thrust faults throughout the region has been established by deep drilling and by geological reconstructions of the regional tectonic deformations. These methods, however, do not usually lead to unique locations and dimensions of such buried faults. The parameters that define the fault rupture producing the January 17 Northridge earthquake were not previously published.

Strong Motion Recordings

Numerous strong motion instruments had been placed by the California Strong Motion Instrumentation Program (CSMIP) and the U.S. Geological Survey. One-hundred and thirty-two of these instruments placed in the free field are within a 100 mile radius of the fault rupture area, [Shakal et al, 1994; USGS, 1994]. The main shock yielded recordings at 193 sites; of these, 116 were free-field recordings, 77 were in engineered

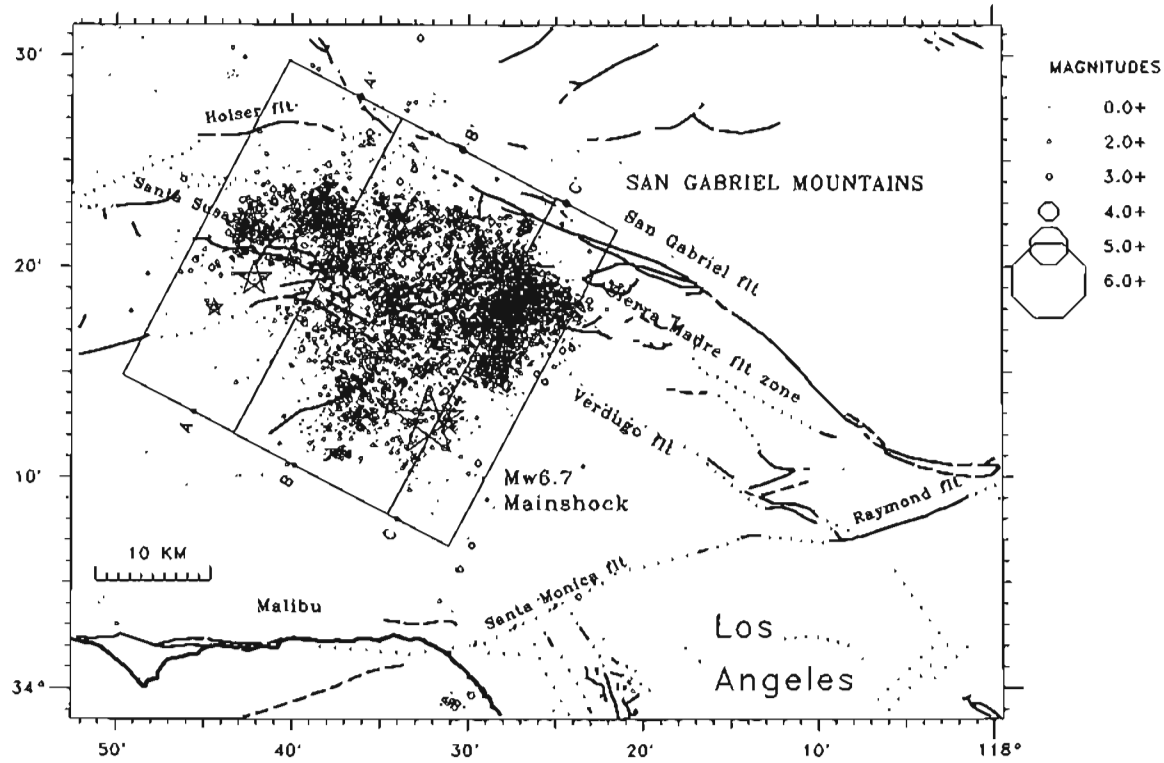

Figure B-1. *Location of hypocenters of the Northridge earthquake and aftershocks. The edge of the aftershock distribution tends to locate the extremes of the fault rupture in the main shock. Figure B-2 shows the depth cross section for the two rectangles A and B.* (data provided by Caltech and USGS, Pasadena, CA; figure provided by Egill Hauksson, Caltech)

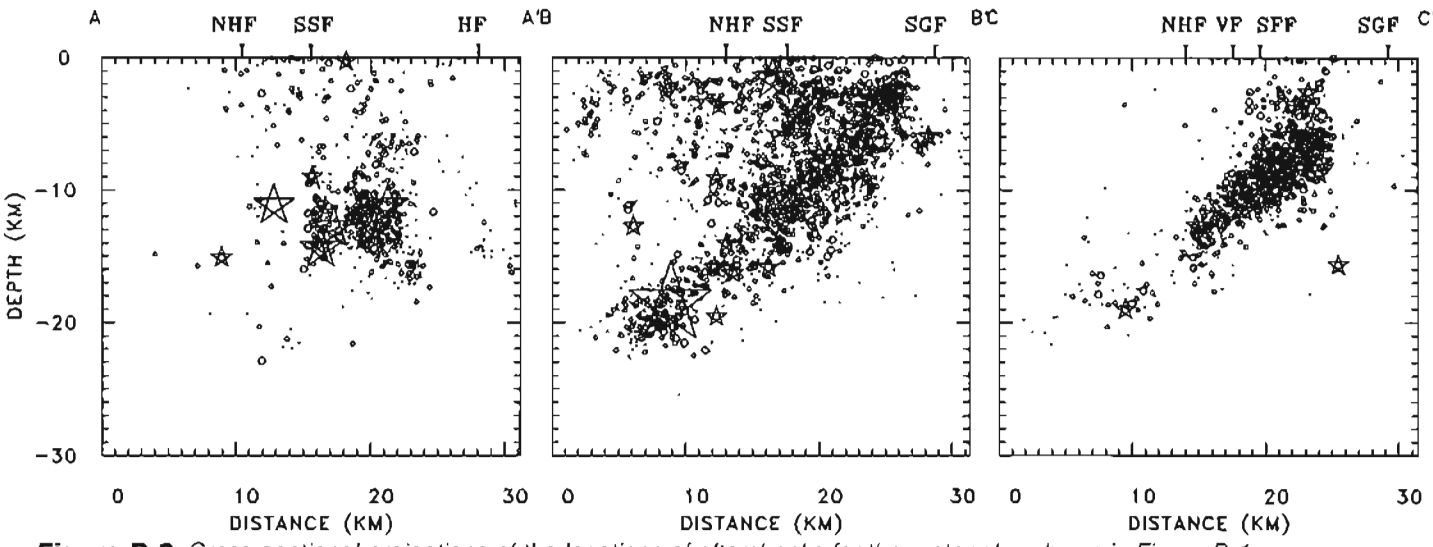

Figure B-2. *Cross-sectional projections of the locations of aftershocks for the rectangles shown in Figure B-1.* (data provided by Caltech and USGS, Pasadena, CA; figure provided by Egill Hauksson, Caltech)

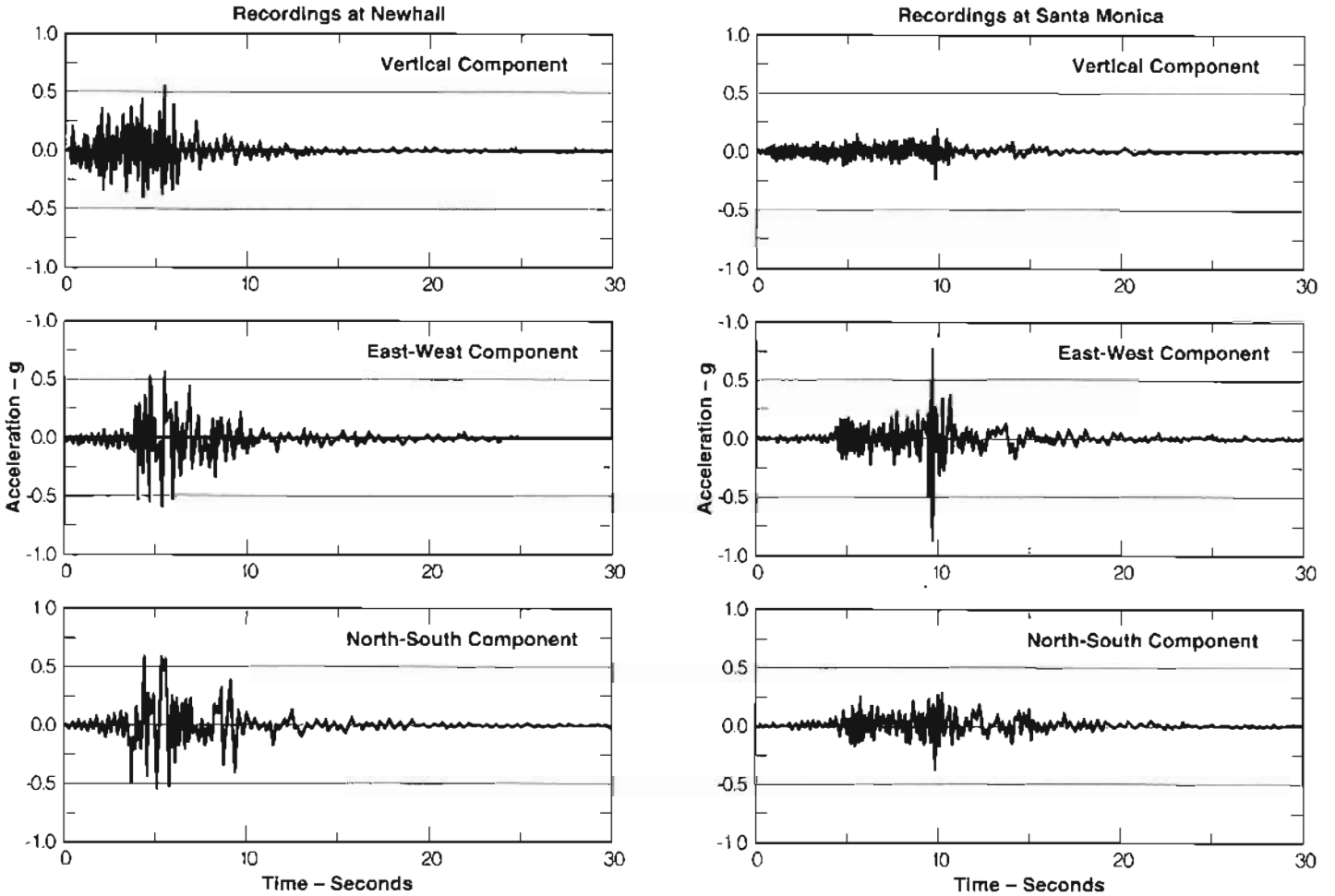

Figure B-3. *Time histories of the ground motions recorded during the Northridge earthquake at the Newhall and Santa Monica stations of the California Strong Motion Instrumentation Program.* (data from Shakal et al, 1994)

structures, including motion recordings from seven bridges [Shakal et al, 1994]. None of the seven bridges that were damaged were instrumented. Figure B-3 shows time histories for two ground motion stations, Newhall (near the I-5/SR-14 failure) and Santa Monica. These records show that the duration of strong motion was about 9 seconds (see Figure 1-1 for approximate locations).

There was, initially, an inference in the media that every where this earthquake produced unusually strong ground motions. The record at the Tarzana site, for example, shows extraordinary duration of strong shaking lasting for about 8 seconds, with a number of peaks measuring 1g. It is likely, however, that there is a special geological or topographic circumstance that explains the high values at this site. Structures near the site do not show damage consistent with such high readings. In the 1987 Whittier Narrows earthquake, the Tarzana site recorded peak accelerations about 12 times larger than the average of a number of nearby sites. Other recordings in the region of strongest shaking suggest maximum values somewhat less than .9g.

Peak horizontal acceleration (PGA) for free field sites is a commonly used measurement to characterize the intensity of ground motion at a site. Figure B-4 shows the variations of PGA with distance from the fault rupture surface for rock and soil sites. The lines on this figure are estimates for a Mw=6.7 earthquake using the attenuation relationship developed by Idriss [1991]. The central line is the median estimate, while the upper and lower lines are the median plus and minus one standard deviation.

Further study of site characteristics will be required to understand these variations. While the recorded values are somewhat higher than the estimation curves, they are not untypical of the scatter observed for

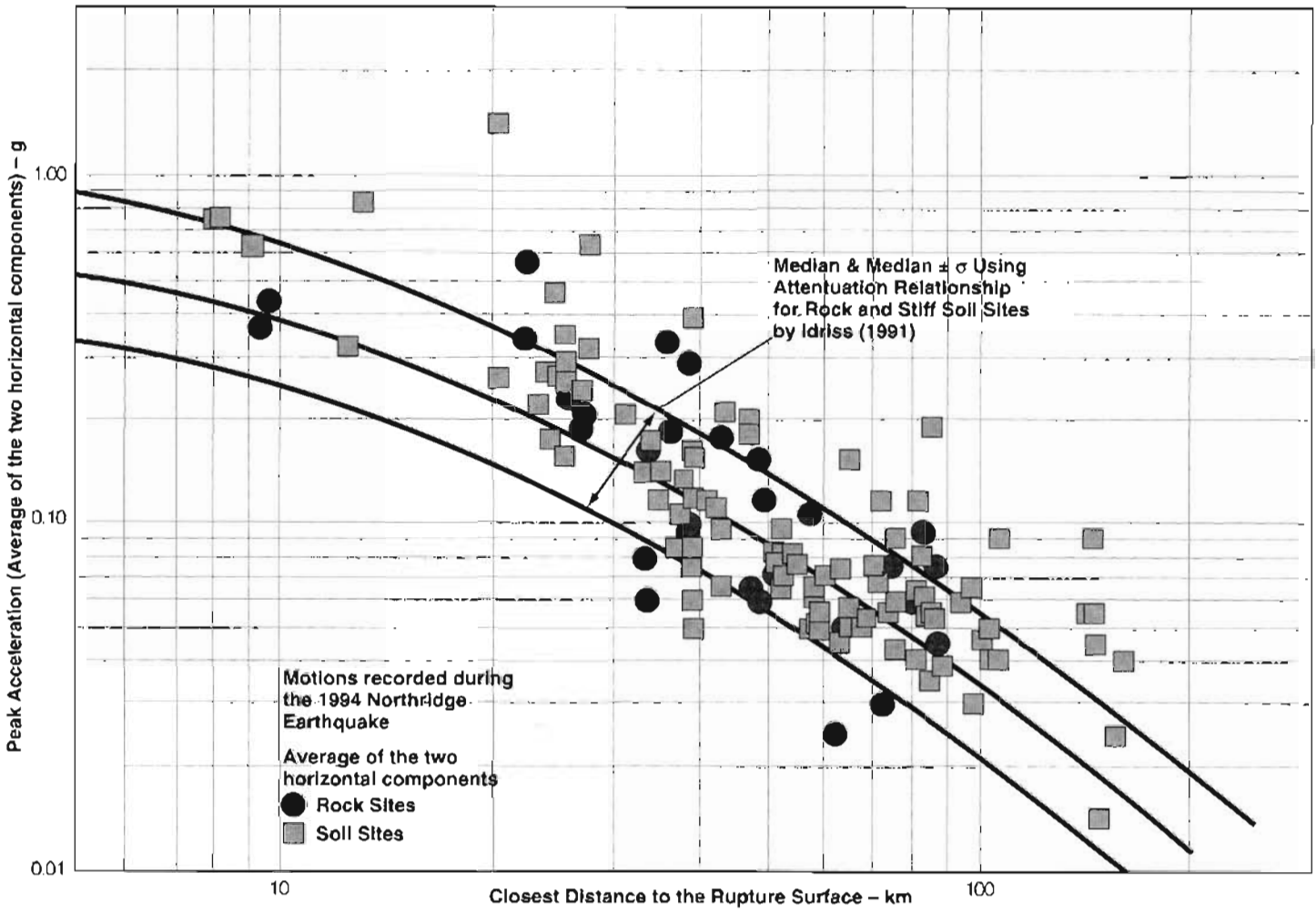

Figure B-4. *Comparison of recorded peak horizontal accelerations with those calculated using the attenuation relationship of Idriss [1991] for rock and stiff soil sites. The measured values are higher than the median estimates using commonly accepted attenuation relationships; the median estimates are about 20% higher, but well within statistical expectations. Soil and rock sites use separate symbols.* (data from Shakal et al, 1994)

other earthquakes. Systematic deviation above and below the median attenuation curve has been observed in several other earthquakes.

There was an early suggestion that vertical accelerations were systematically higher in the Northridge earthquake than was expected based on earlier recordings of similar-sized earthquakes in California. The normal assumption in building code and engineering practice is that the vertical to horizontal PGA ratio is 2/3. Figure B-5 shows that the average trend for this ratio for all distances is approximately 2/3 in average for small distances and less for greater distances.

An important method for characterizing the seismic excitation used in design is the response spectrum. Normalized spectra are given in Figure B-6 for a group of soil sites so that the general nature of the ground motions can be compared. These show a considerable scatter as is quite typical for such plots. The ARS spectrum used by Caltrans for design at sites with 10 to 80 feet of alluvium are also shown. Many of the sites used probably do not fall in this category; when further information is available on site conditions where recordings were written. For low periods, the recorded spectra are systematically higher than the ARS spectra; at medium to high periods, in excess of 0.5 seconds, the ARS spectrum is comparable to the average of the soil site spectra given.

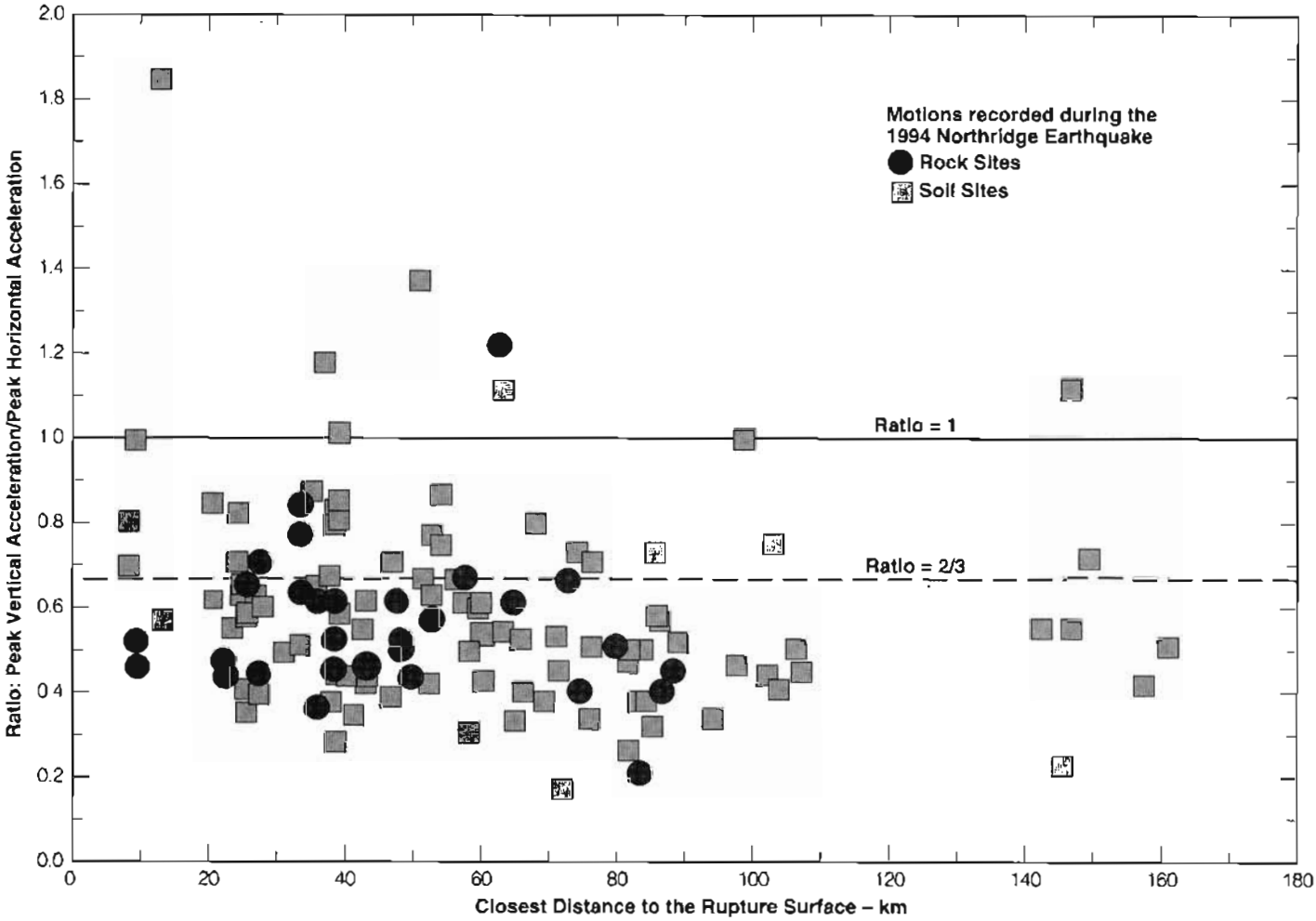

Figure B-5. *Variations of the ratio of peak vertical accelerations to the average peak horizontal acceleration versus the closest distance to the fault rupture surface.* (data from Shakal et al, 1994)

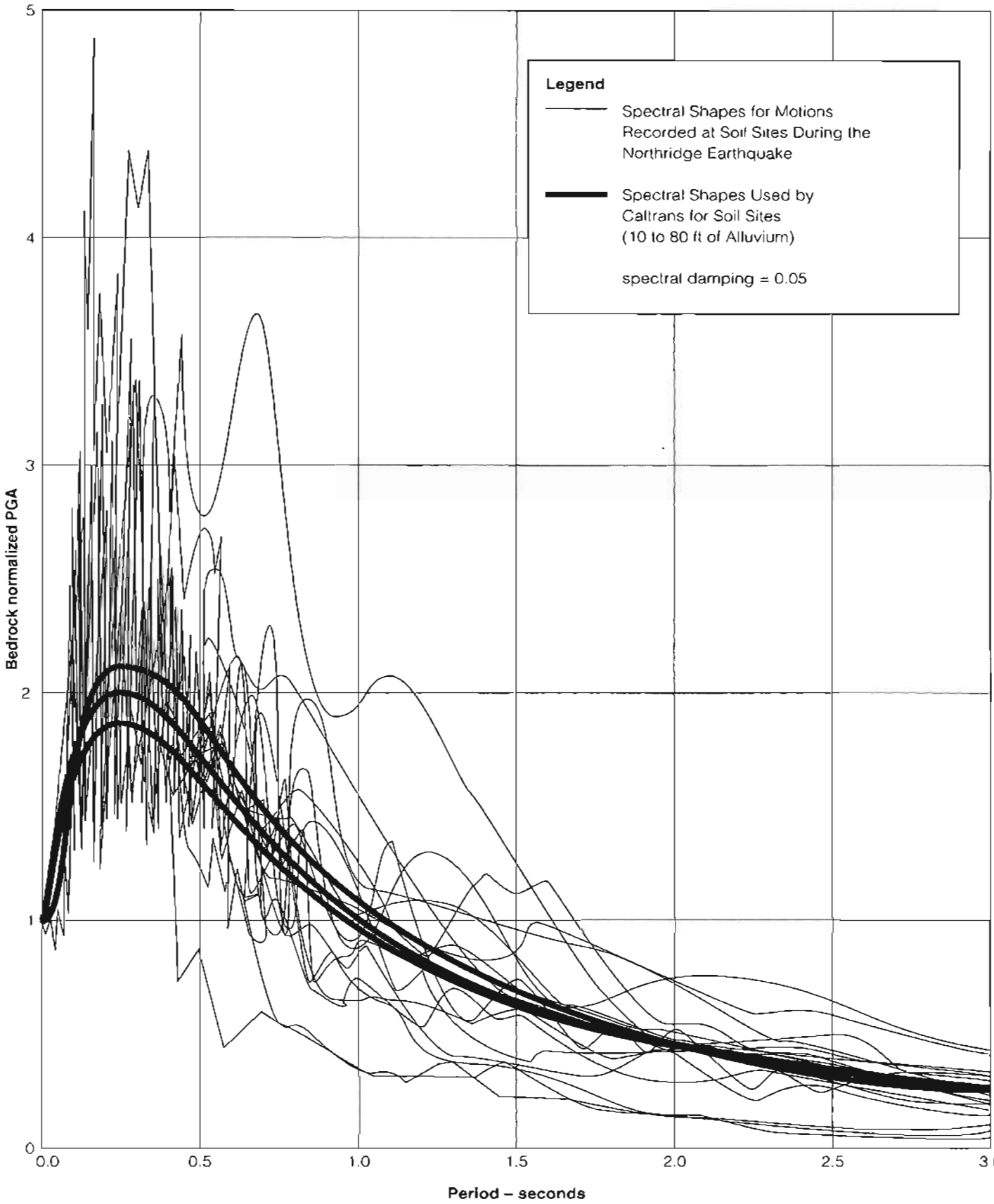

Figure B-6. *Normalized standard response spectra for selected soil sites as measured in the Northridge earthquake The ARS spectrum used by Caltrans is given for comparison.*

Table B-1. *Locations of bridges for which strong motion records were obtained in the Northridge earthquake from the CSMIP program.* (data from Shakal et al, 1994)

Location	Highway	Distance from epicenter (km)	Site type	Maximum acceleration Ground	Structure
Los Angeles	I-10/405 Inter-change Bridge	22	deep alluvium	NA	1.83g
Los Angeles	Vincent Thomas Bridge	57	alluvium	.25g	.65g
Devore	I-15/215 Inter-change Bridge	104	deep alluvium	.08g	.24g
San Bernardino	I-10/215 Inter-change Bridge	116	deep alluvium	.13g	.47g
Beaumont	I-10/60 Inter-change Bridge	146	alluvium over granite bedrock	.04g	.09g
North Palm Springs	I-10/62 Inter-change Bridge	181	deep alluvium	.02g	.11g

Strong Motion Records from Bridges

Strong motion records were obtained from six bridges during the Northridge earthquake at distances ranging from 22 km (14 mi) to 181 km (115 mi). Table B-1 lists the bridges, their locations and maximum accelerations observed. Only one instrumented bridge was in the region of strong shaking (the I-10/405 Interchange), and one in the region of moderate shaking (Vincent Thomas).

The most significant record is from the I-10/I-405 interchange. It is a 1037 feet long, curved concrete box girder structure. It has nine single-column bents and two open-seated abutments. The bridge was retrofitted in 1991 with steel jackets on some columns. Installation of instruments was completed, funded by Caltrans, just before the earthquake. A peak acceleration of 1.83g was recorded at the box girder near the west abutment. This bridge is located about 4 miles west of the section of the I-10 Freeway that collapsed. The bridge did not suffer any significant damage.

These are the instrumented bridges that recorded the Northridge earthquake. The I-10/405 record is of great importance since it is for a retrofitted bridge near the epicenter. The focus of the instrumentation program is on complex geometries and retrofitted bridges. Some consideration should be given to instrumenting unretrofitted bridges and more common types of bridges. Records from these types of structures would provide a basis for understanding how retrofitting is affecting bridge performance. Caltrans has steadily increased its commitment to the CSMIP program for bridge instrumentation. The increase from $40,000 in 1988 to $1,000,000 per year starting in July, 1994 should give the opportunity for significant improvements. While a few additional bridges in northern and southern California have been instrumented to date, much of the instrumentation effort is yet to be completed, particularly for toll bridges.

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Appendix C

San Fernando Earthquake, 1971

The 1971 San Fernando main shock was one of the most important earthquakes in the development of modern seismic design and retrofitting practices—for bridges as well as for buildings. The earthquake (M_W=6.7) of February 9, 1971, caused 53 deaths and an estimated damage of less than $1 billion in 1971 dollars.

By comparison, the Northridge earthquake, with magnitude 6.7, occurred in a populated area, caused 56 deaths, and estimated damage of $15-30 billion. Each of these earthquakes caused major damage and the collapse of several buildings, bridges, and other structures. Each event has had and will continue to have a major effect on the improvement of the seismic design and retrofit procedures for Caltrans bridges in California.

Previous design practices were demonstrated to be deficient in the San Fernando earthquake. This section reviews the earthquake's impacts on bridges and how Caltrans responded to the discovery that their seismic design practices needed revision. The 1971 San Fernando earthquake is of great importance in the study of the behavior of Caltrans structures because its size and fault type is similar to the Northridge earthquake, and it occurred on a neighboring thrust-fault to the north of the Northridge fault rupture.

Seismic Characteristics of the San Fernando Earthquake

The San Fernando earthquake epicenter was in a lightly populated area at the edge of a San Fernando Valley. It occurred at 6:07 AM on February 9, 1971, with a hypocenter of latitude 34° 24'.0N, longitude 118° 23'.7W and focal depth of about 13 km (Figure C-1). Its moment magnitude was calculated at M_W = 6.6. Surface faulting occurred in the San Fernando Valley and in the foothills of the San Gabriel Mountains, particularly in Sylmar. The surface faulting had both thrust and left-lateral motions. The strike varied from place to place with a mean value N70° W and a dip of 45°. The total length of surface faulting was approximately 15 km, with some lateral offsets. In striking contrast to its 1994 seismogenic neighbor, the slip fault in this case dipped to the north under the San Gabriel Mountains.

Although the San Fernando earthquake was of moderate magnitude, accelerograph measurements and observed damage to engineered structures indicate that the intensity of surface ground shaking in the immediate vicinity of the epicenter was considerably higher than predicted at that time for such an event. The highest recorded peak ground accelerations (PGA) measured by the San Fernando earthquake, equal to 1.26g horizontally and 0.72g vertically, were recorded on a rock ridge near the abutment. This PGA was significantly greater than any previous recordings. At the sites of the five collapsed freeway structures, the horizontal PGA levels were estimated to be approximately 0.6g, which was considered to be near the upper-bound value at that time.

Damage to Freeway Structures

I-5/I-210 Interchange. The most dramatic of all bridge damage caused by the San Fernando earthquake occurred at the Golden State Freeway (Interstate 5) and

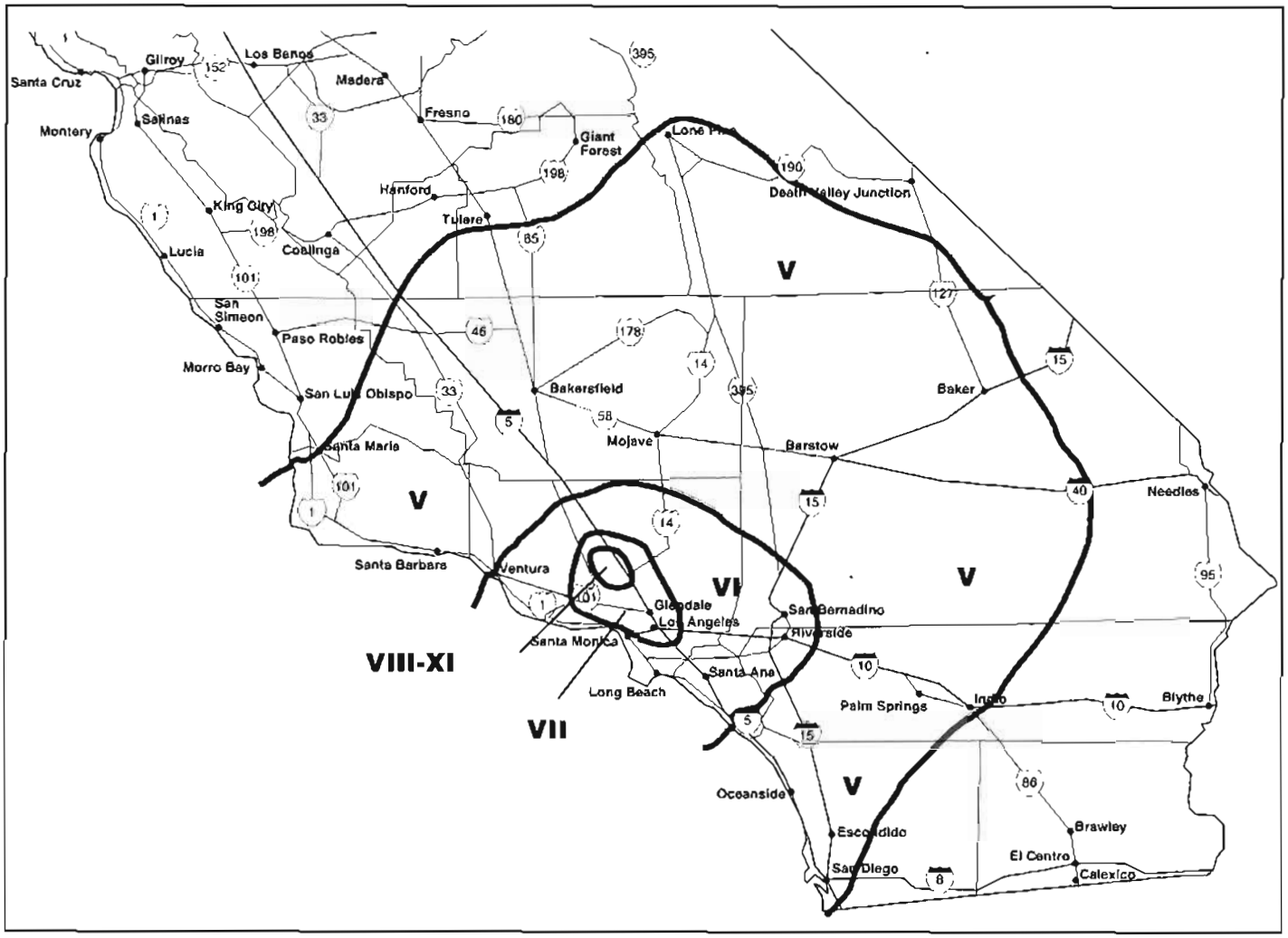

Figure C-1. *Location of the 1971 San Fernando earthquake. Roman numerals indicate the Modified Mercalli Intensity; see Figure 3-1 for description of the intensity levels.*

Foothill Freeway (Interstate 210) Interchange. The highest overcrossing at this site, which carried southbound traffic from Foothill Freeway onto the Golden State Freeway collapsed during the earthquake (Figure C-2). The box girder deck of this overcrossing (approximately 770 feet in length) was supported on six piers and end abutments. The two most southerly piers were supported on spread footings which, in turn, were supported on driven concrete piles. The four most northerly piers were supported directly on a single round pile cast directly in a 6-foot diameter drilled hole. The box girder had one expansion joint near mid-crossing in addition to those at the abutments.

The two principal causes of collapse of this particular overcrossing were:

1. The large vibratory motions induced in the superstructure by the high intensity ground motions.
2. The relative ground displacements that occurred between abutment supports.

Considering the locations and orientations of the abutments and expansion joints, and considering the general form of the deck curvature in plan view, it is quite apparent that the deck was highly constrained against large displacements in all directions except in the westerly direction. As the vibratory motions of the deck built up with considerable bias in the that direction, the deck separated at the centrally located expansion joint, allowing one end of a span to fall off its support and initiate collapse of the entire structure.

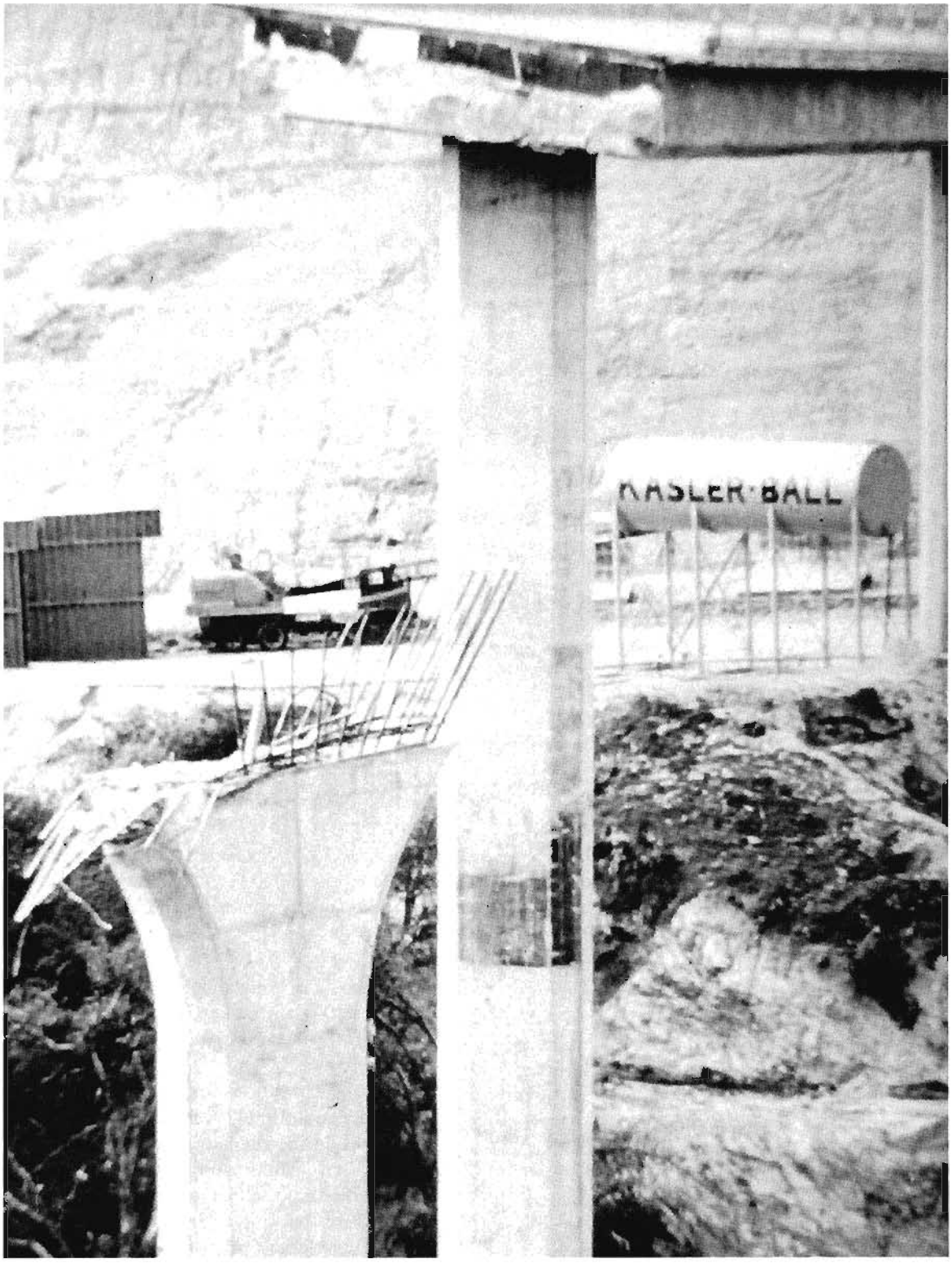

Figure C-2. *The most dramatic of all bridge damage caused by the San Fernando earthquake occurred at the Golden State Freeway (I-5) and Foothill Freeway (I-210) Interchange. The highest overcrossing at this site, which carried southbound traffic from Foothill Freeway onto the Golden State Freeway, collapsed during the earthquake. Note the similarity to the performance of the I-14/I-5 connection overcrossing in the Northridge earthquake, Figure 4-2.* (photo: National Earthquake Engineering Information Service archive)

Figure C-3. *Columns of the San Fernando Road Overhead suffered heavy damage during the San Fernando earthquake. Note the similarity to the performance of the I-118 Mission and Gothic undercrossing in the Northridge earthquake, Figure 4-6.* (photo: National Earthquake Engineering Information Service archive)

I-5/State Highway 14 Interchange. Another dramatic collapse occurred during the earthquake at the Golden State Freeway (Interstate 5)and State Highway 14 Interchange, where several overcrossings were still under construction. A long (approximately 400-ft) central section of the highest overcrossing (completed before the earthquake) collapsed. This long, prestressed concrete section of bridge deck was supported at each end on bearing pads at expansion joints and by a single column standing 160 feet high. The initial cause of collapse was the large relative deck displacement at one expansion joint, which allowed the box girder to fall off its support and initiate collapse of the entire central section. Both cantilevered portions of the deck, as they hinged down, broke off at the top of the central column, which allowed them to fall almost straight down from their original positions. The central column then fell to the west. This interchange was damaged again in the Northridge earthquake (see Section 3).

San Fernando Road Overhead. The San Fernando Road Overhead suffered heavy damages during the San Fernando earthquake. One span crossing the Southern Pacific Railroad fell from its bearing support at one end, causing it to collapse (Figure C-3). The deck of other spans remained in place; though their supporting columns were badly damaged. Many of the stiffer columns suffered shear failures, while the more flexible columns suffered heavy flexural damages at their tops. The main reinforcing bars at these locations buckled due to the high compressive forces produced by the earthquake. Once the concrete coverage spalled off the bars, the ties were inadequate

to provide their needed lateral constraint and to provide confinement to the core concrete. Other forms of damage to the San Fernando Road Overhead included the dislodging of steel rocker bars from their support assemblies. These failures were caused by the large relative displacements produced between deck and support.

Other Damage. Other freeway structures that suffered light to heavy damages during the San Fernando earthquake were:

- Foothill Boulevard Undercrossing at the Foothill Freeway
- Roxford Street Undercrossing at Foothill Freeway
- Polk Street Undercrossing at Foothill Freeway
- Hubbard Street Undercrossing at Foothill Freeway
- Bledsol Street Undercrossing at Foothill Freeway
- Tyler Street Pedestrian Overcrossing at Foothill Freeway
- Culvert under Foothill Freeway
- Via Princessa Undercrossing on State Highway 14
- Santa Clara Overhead Crossing on State Highway 14

The types of damages to these structures included:

1. Flexural yielding and crushing of concrete at tops of columns.
2. Shear fracturing of columns followed by crushing of concrete causing main reinforcing bars to buckle outward.
3. Fracturing of piles supporting abutments.
4. Wing walls broken away from abutments.
5. Differential settlement of soils behind abutments.
6. Flexural cracking in diaphragm abutments.
7. Breakage of concrete due to pounding at expansion joints.
8. Downward slippage of concrete aprons at abutments.

Design Improvements

The 1971 San Fernando earthquake experience, made it clear that the freeway structures then existing had serious deficiencies. The damages caused by the earthquake pointed out the need to improve design details as follows:

1. **Expansion Joints:** Collapse of high overcrossings was initiated by bridge spans falling off their supports at abutments and expansion joints due to excessive displacements of the spans relative to their bearing supports at expansion joints and at abutments. These needed to be widened to provide more effective ties across expansion joints, and eliminate expansion joints wherever feasible.
2. **Columns:** Inadequate ties, both in size and spacing, contributed to shear and flexure-type failures in the columns. Design details, particularly the size and placement of reinforcing bars and ties had to be improved. Such changes were critical to satisfactory performance under maximum seismic loading conditions.

3. **Column Caps:** Damages indicated a lack of reinforcing bars tying column caps to their respective box-girder bridge decks. Design details, again, had to be improved.
4. **Column Foundations:** Failures at the bases of columns using single cast-in-place piles or spread footings with driven piles showed inadequate anchorage of the main reinforcing bars. Corrective measures had to be taken so that sufficient anchorage was provided to develop the full strength of the main reinforcing bars.
5. **Abutments and Wing Walls:** Abutments and wing wall failures caused by excessive dynamic forces transmitted by backfill earth pressures and seismic deck forces showed the need to strengthen these elements so that they would perform satisfactorily under maximum expected seismic conditions.

Appendix D

Loma Prieta Earthquake, 1989

In the evaluation of the damage to structures, particularly freeway overpasses and bridges, the second earthquake for comparison is the Loma Prieta earthquake of October 17, 1989, which occurred in central California, 60 miles south of San Francisco. The Loma Prieta earthquake (Mw=7.0) occurred in a lightly populated area in the Santa Cruz mountains, caused 62 deaths, and estimated damage of $6-7 billion in 1989 dollars.

The Loma Prieta earthquake caused the most damage of any California earthquake since the 1906 earthquake. Northridge now has this distinction. Loma Prieta caused extensive damage to seven double-decker viaducts, including the Cypress Viaduct, which failed. Damage closed the San Francisco-Oakland Bay Bridge for one month.

Seismic Characteristics of the Loma Prieta Earthquake

The epicenter was located approximately 16 km northeast of the city of Santa Cruz. The focal depth was approximately 18 km below the surface, with a fault plane dipping about 10° from the vertical to the west. While it was originally thought to have occurred by slip of the San Andreas fault, some geologists and seismologists now believe that it occurred by rupture of a fault to the west of the San Andreas. Analysis of seismograms showed that the rupture spread about 20 km to the north and 20 km to the south, with seismic waves radiating for 8 seconds from the moving slip fronts. Like the Northridge earthquake source, the Loma Prieta rupture also propagated toward the earth's surface but stopped at a depth of approximately 5 km. The direction of slip was of oblique nature with a right lateral offset of about 2 m and a vertical offset of about 1.5 m. It can be termed a blind oblique slip earthquake source.

Impact of the Loma Prieta Earthquake on Bridges

Only a small percentage of the bridges in the area sustained any earthquake damage at all. Moreover, most of the bridges damaged in this earthquake were constructed before 1971, before construction standards were stiffened to reflect lessons learned in the 1971 San Fernando earthquake. The greatest damage during the Loma Prieta earthquake occurred to older structures on soft ground.

Caltrans District 4, whose jurisdiction approximates the area of greatest Loma Prieta earthquake damage, is responsible for 1,896 state bridges, of which 91 (4.8 percent) incurred some degree of damage (mostly minor) during the earthquake. Structural damage or the potential threat to public safety was sufficiently serious in the case of 13 state bridges that they were closed to traffic for some time. Table D-1 lists the Caltrans bridges that sustained major damage.

The level of ground shaking in the Loma Prieta earthquake was (for most bridges in the Bay Area) smaller in both duration and intensity than would be expected in larger and closer earthquakes. Moreover, the duration was not sufficient to excite all of the different modes of the Bay and Golden Gate Bridges that would be excited in a longer-duration event, nor was the level of shaking sufficiently close to that expected in major

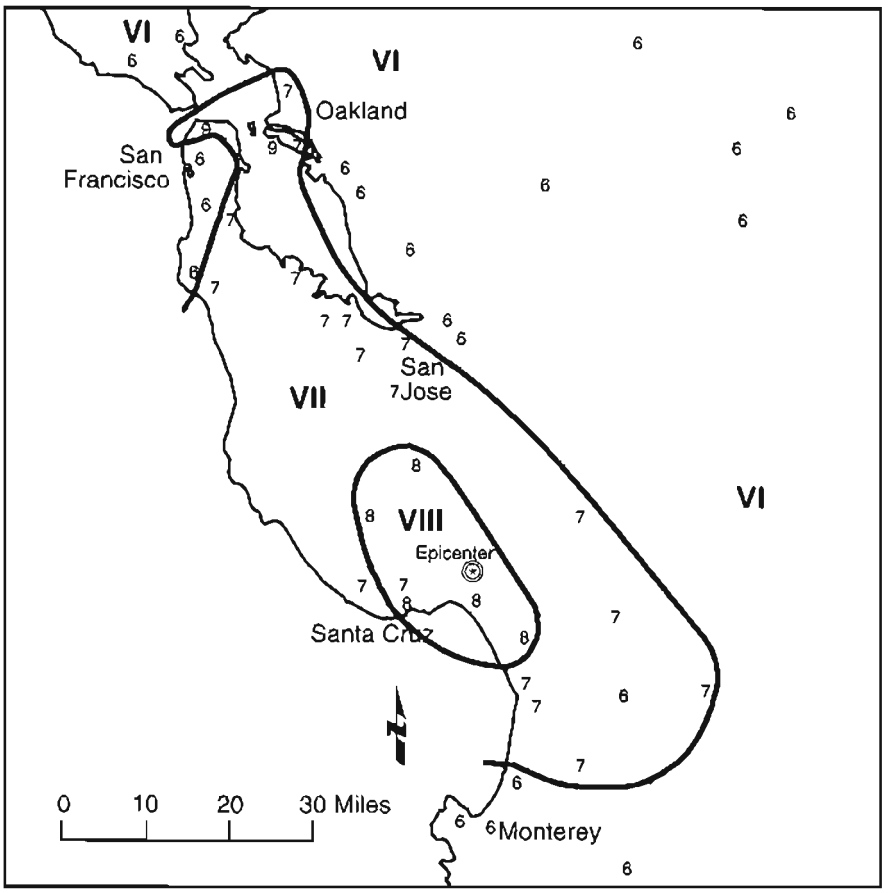

Figure D-1. *Isoseismal map of the damage impacts of the Loma Prieta earthquake. See Figure 3-1 for the definitions of MMI levels.*

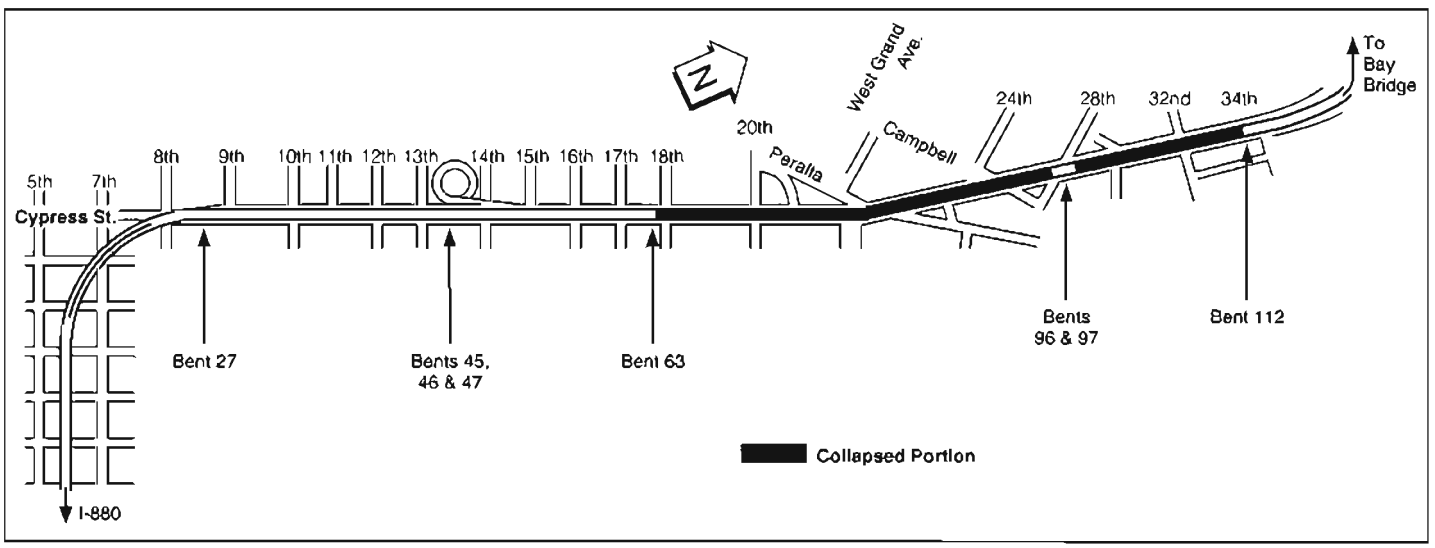

Figure D-2. *The Cypress Viaduct showing the extent of the collapse during the 1989 Loma Prieta earthquake.* (Housner 1990)

earthquakes. Loma Prieta was, then, a limited test of the strengths of bridge elements.

The most tragic impact of the earthquake was the life loss caused by the collapse of the Cypress Viaduct (Figure D-2), while the most disruption was caused by the closure of the Bay Bridge (Figure D-3) for a month, leading to costly commute alternatives and probable economic losses. In addition, some of the steel rocker bearings supporting the navigator spans of the San Mateo-Hayward Bridge failed. Any one or all of these could have led to catastrophic damage if shaking had been longer or more intense.

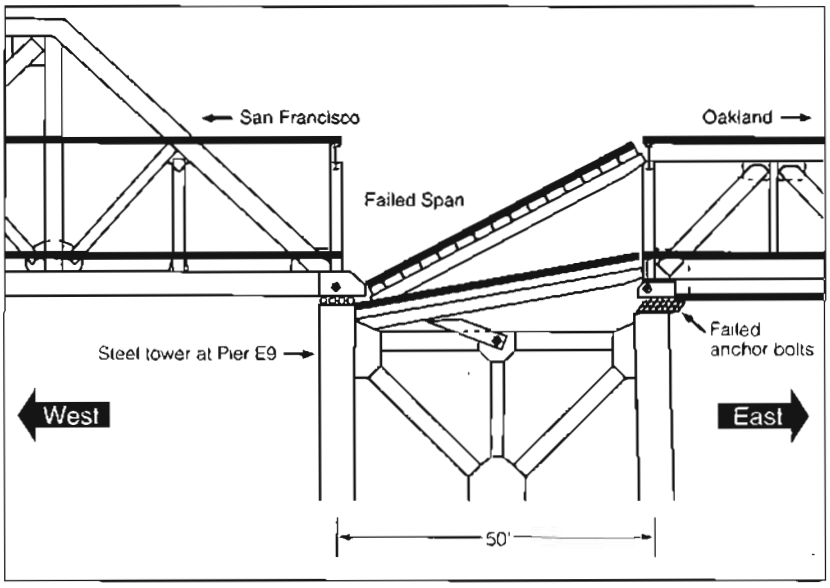

Figure D-3. *The west sections of the San Francisco-Oakland Bay Bridge fell during the Loma Prieta earthquake. The upper and lower closure spans fell when the bolts attaching the east (right) truss-span were severed and it moved to the east, pulling the link spans off their western supports.* (Housner 1990)

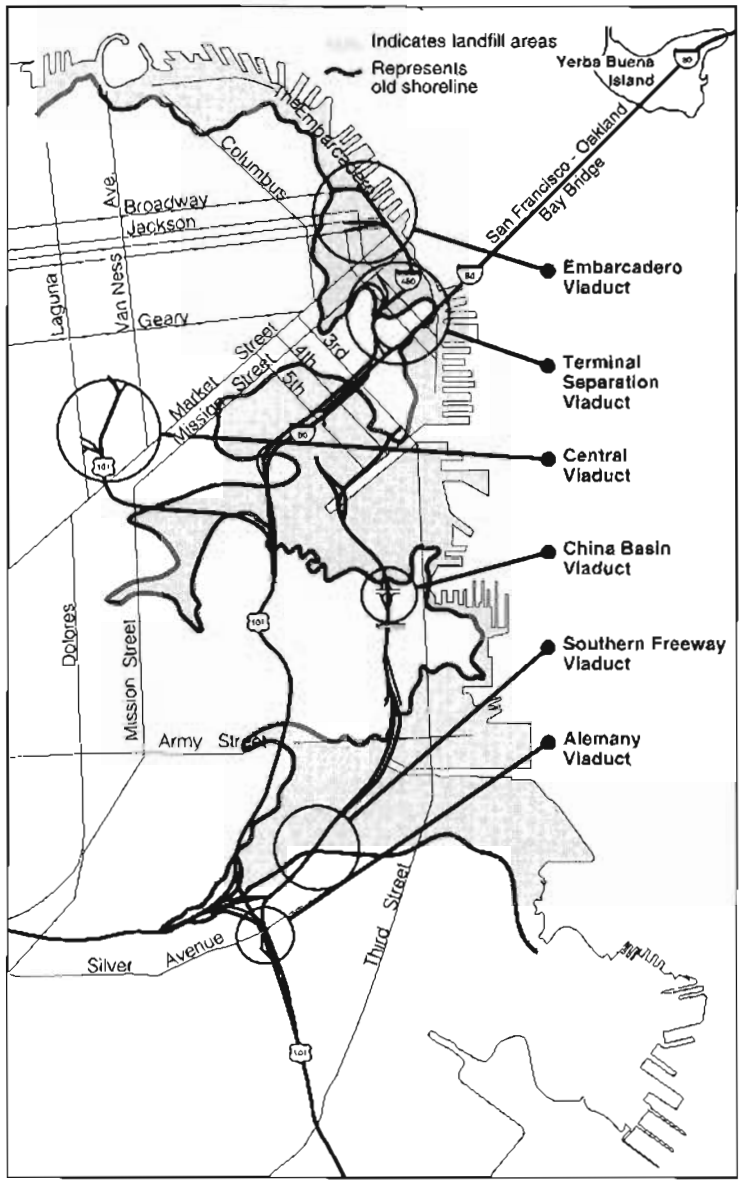

Figure D-4. *Location of the San Francisco freeway viaducts damaged in the 1989 Loma Prieta earthquake. The shaded areas are filled portions of the bay within the original shoreline.* (Housner 1990)

The Loma Prieta earthquake was, for the San Francisco freeway viaducts, a minor-to-moderate earthquake in ground motions. The viaducts, however, suffered major damage. These viaducts (Embarcadero Freeway, Terminal Separation Viaduct, Central Viaduct, China Basin Viaduct, Southern Freeway Viaduct and Alemany Viaduct) in San Francisco (Figure D-4) were all built with the same technology used for the Cypress Viaduct and are the only structures in the state of this design. All the freeway structures, with the exception of the Alemany Viaduct, were damaged during the earthquake and subsequently closed to traffic.

Bridges maintained by local governments also incurred damage, though none as catastrophic as that sustained by some of the Caltrans structures. A partial survey by Board of Inquiry staff found that at least 43 locally maintained structures in the earthquake area were damaged, of which at least 5 were closed to traffic for some time. None, however, collapsed. Reports from post-earthquake reconnaissance teams indicated that most local bridges performed remarkably well.

Table D-1. *Caltrans bridges sustaining damage greater than $100,000 during the Loma Prieta earthquake. Conditions are as of May 1, 1990.* (Housner 1990)

Name of Bridge	Location	Description of Damage
Bridges Closed to Public Traffic after the Earthquake:		
San Francisco-Oakland Bay Bridge (I-80)	San Francisco Bay (Alameda Co.)	Upper and lower closure spans at Pier E9 fell; spans at Pier E23 were near failure; concrete pedestal base of Pier E17 cracked; connection bolts at Piers E-17 through E-23 damaged; opened for traffic after one month; 1 death and 12 injuries.
Cypress Street Viaduct (I-880)	Oakland (Alameda Co.)	Collapse of 48 bents, causing the upper roadway to collapse onto the lower roadway; 41 deaths and 108 injuries with 1 subsequent death; demolished, reconstruction uncertain.
Struve Slough Bridge (SR 1)	Santa Cruz County	Extensive collapse of the "twin" bridges; opened on January 25, 1990 after reconstruction.
West Grand Avenue Viaduct (I-80)	Port of Oakland (Alameda Co.)	Damage to bents, columns and earthquake restrainers; open to traffic after several days.
Southbound connector over-crossing (I-980)	West Oakland (Alameda Co.)	Damage to two outrigger bents; opened on October 23, 1989.
Mora Drive over-crossing (I-280)	Santa Clara County	Damaged column requiring reconstruction; opened to traffic after a few hours.
Central Freeway Viaduct (US 101)	San Francisco	Damage to bents and columns; retrofit required; portions are still closed.
Southern Freeway Viaduct (I-280)	San Francisco	Damage to bents; retrofit required; still closed to traffic.
China Basin Viaduct (I-280)	San Francisco	Damage to bents; retrofit required; opened to traffic after 6weeks.
Terminal Separation Viaduct (I-480)	San Francisco	Damage to steel span bearings; retrofit required; still partially closed to traffic.
Embarcadero Viaduct (I-480)	San Francisco	Damage to bents and columns; retrofit required; still closed to traffic.
Route 92/101 Interchange (US 101)	San Mateo County	Damage to bearings, expansion joints, footings, and columns; opened to traffic after 2 weeks.
San Mateo-Hayward Bridge (SR 92)	Between San Mateo and Alameda Counties	Failure of steel rocker bearings; opened to traffic after a few hours.
Other Bridges Requiring Major Repairs after the Earthquake:		
Temescal Creek (I-80)	Alameda County	Several large cracks in concrete box culvert walls and ceiling.
Distribution structure (I-580)	Alameda County	Damage to bent caps and columns.
Distribution structure (I-580)	Alameda County	Damage to bent caps and columns.
Fifth Avenue over-crossing (I-880)	Alameda County	Damage to columns, bent caps, bearings, and substructure.
Route 242/680 separation (SR 242)	Contra Costa County	Damage to bearing system at Bent 4.
West connector over-crossing (SR 242)	Contra Costa County	Cracks and spalls; damage to bearings and joint seals.
Benicia-Martinez Bridge (I-680)	Contra Costa County	Damage to open deck expansion joints.
Richardson Bay Bridge (US 101)	Marin County	Damage to bearings, caps, columns, and earthquake restrainers.
Pajaro River Bridge (US 101)	Santa Clara County	Anchor bolt and expansion joint damage; cracks and spalls.
Alemany Viaduct (I-280)	San Francisco	Spalling and column damage; retrofit required.
Napa River Bridge (SR 37)	Solano County	Superstructure shifted 4" longitudinally; earthquake restrainers damaged.

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Authors' Affiliations

Bruce A. Bolt
University of California, Berkeley

Nicholas F. Forell
Forell/Elsesser Engineers, San Francisco

George W. Housner
California Institute of Technology

I. M. Idriss
University of California, Davis

Joseph P. Nicoletti
URS Consultants, San Francisco

Joseph Penzien
International Civil Engineering Consultants, Berkeley

Alexander C. Scordelis
University of California, Berkeley

Frieder Seible
University of California, San Diego

Charles C. Thiel Jr.
Telesis Consultants, Piedmont