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Report to Congressional Requesters

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TRANSPORTATION INFRASTRUCTURE:

The Nation's Highway Bridges Remain at Risk From Earthquakes

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Resources, Community, and
Economic Development Division

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January 23, 1992

The Honorable Quentin N. Burdick
Chairman
The Honorable John H. Chafee
Ranking Minority Member
Committee on Environment and Public Works
United States Senate

The Honorable Daniel P. Moynihan
Chairman
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Ranking Minority Member
Subcommittee on Water Resources,
Transportation, and Infrastructure
Committee on Environment and Public Works
United States Senate

The Loma Prieta Earthquake, which struck northern California in October 1989, graphically demonstrated the devastating impact an earthquake can have on highway bridges not adequately protected against seismic forces. The Cypress Viaduct and a section of the Bay Bridge connecting Oakland and San Francisco both collapsed, killing 43 people. The earthquake also damaged 95 other bridges. The federal cost to help California correct the bridge damage is expected to reach $1 billion. Since California is considered a leader in seismic bridge design and retrofit, concerns have been raised about the safety of bridges in other states subject to earthquake forces and the role of the Federal Highway Administration (FHWA)—an agency of the Department of Transportation—in addressing bridge seismic safety.

In response to your August 3, 1990, request and subsequent agreements with your offices, we determined (1) which states have areas where bridges may be damaged by moderate- to high-intensity earthquakes; (2) what actions states have taken to identify and correct seismic-related bridge deficiencies; and (3) what actions FHWA has taken, or needs to take, to assist states in addressing seismic deficiencies in bridges. Although we focused on the threat that earthquakes pose to the nation's bridges, we recognize that seismic vulnerability is only one of the many bridge conditions that may threaten the safety of highway users daily.

In 1991, FHWA reported that about 226,000 of the nation's 577,000 bridges (39 percent) are structurally or functionally deficient.[1]

Results in Brief

Thirty-one states have bridges that are at risk from ground shaking induced by moderate- to high-intensity earthquakes. Earthquakes need not be severe to cause bridge damage. For example, in Memphis, Tennessee, a city located near the New Madrid fault zone, modeling indicates a moderate-intensity earthquake would likely damage over one-third of the bridges in the metropolitan area. Experts estimate that this fault zone has a 40- to 63-percent chance of a moderate earthquake in the next 15 years.

FHWA has encouraged states, particularly those subject to moderate- or high-intensity earthquakes, to identify and strengthen (retrofit) existing bridges on important defense and evacuation routes, and on main commuter and commerce routes. Despite this federal encouragement, states have made limited progress in identifying and correcting seismic-related bridge deficiencies. We surveyed 26 of the 31 states with areas at seismic risk. Eight of the 26 states had completed their identification of vulnerable bridges. Three of the 8 states had retrofitted, or were in the process of retrofitting, less than 2 percent of these bridges. State bridge officials gave a number of reasons for limited action, including limited funding, a lack of technical information available for seismic retrofit work, and a belief that their state had a low risk of earthquake damage.

The seismic vulnerability of the nation's bridges—including bridges along routes vital for national defense, commerce, or emergency response—is largely unknown. Although FHWA requires states to report annually on the overall structural condition of their bridges, they are not required to identify bridges subject to seismic forces. Because the degree of seismic risk varies among states, FHWA's role has been to facilitate state seismic efforts by providing states with procedural guidance and training, as well as by supporting seismic research efforts. But according to state bridge officials, additional FHWA actions are needed in these areas because most states lack experience and expertise in addressing seismic bridge deficiencies. Also, states were concerned that they may not have the latest information on seismic research and

[1] According to FHWA, most bridges that are structurally deficient are not in danger of collapse, but they are likely to have a limit on the loads they support and require heavy vehicles to take an alternative longer route. Functionally deficient bridges either do not have adequate lane widths, shoulder widths, or vertical clearances to serve the traffic demand or their waterways may be inadequate and may sometimes allow flooding of the roadway.

retrofit techniques. Without such information, a state could use an outdated retrofit technique or duplicate research conducted by other states or various federal agencies.

Background

The Highway Bridge Replacement and Rehabilitation Program (HBRRP) is the primary source of federal funding for the nation's bridges.[2] For fiscal years 1987 to 1991, the Congress authorized $8.1 billion for HBRRP. The bridge program is administered by FHWA. In consultation with the states, FHWA inventories and classifies all federal-aid bridges according to their condition in order to determine their eligibility for HBRRP funds. FHWA officials said that the potential for seismic-related structural damage is not considered in the apportionment of HBRRP funds, since federal bridge funds are apportioned according to existing physical characteristics of bridges.

Historically, bridges in the United States have proven vulnerable to earthquakes and, in some cases, have been totally destroyed when the superstructures collapsed from their supporting elements. California—considered a leader in seismic design for new-bridge construction and retrofit of existing bridges—included seismic considerations in its bridge design specifications as early as 1940. However, during the 1971 San Fernando, California, earthquake, which damaged more than 60 bridges, the inadequacy of the existing design criteria was exposed, particularly in bridge deck and support column design features.

As a result, during the 1970s FHWA funded seismic research to develop new seismic design standards. In 1983 these standards—"Guide Specifications for the Seismic Design of Highway Bridges"—were adopted by the American Association of State Highway and Transportation Officials (AASHTO) as guidelines for states to consider in designing highway bridges. In 1991, the guidelines were incorporated into AASHTO's "Standard Specifications for the Design of Highway Bridges." AASHTO promulgates national bridge design standards that FHWA requires for use on federally funded bridge projects.

Existing bridges that are located in areas subject to earthquakes and are not built to withstand seismic forces may need to be retrofitted to overcome deficiencies that could lead to damage or collapse during an earthquake. However, given the difficulty and cost involved in strengthening

[2] Seismic retrofit work also can be funded from four principal federal-aid highway programs, according to FHWA officials.

an existing bridge to new design standards, a retrofit effort of this magnitude may not be economically feasible. For this reason, the primary goal of seismic retrofit is to minimize the risk of unacceptable damage during an earthquake. Damage is not acceptable, according to FHWA, if it results in the collapse of all or part of the bridge, or if a vital transportation route that passes over or under the bridge can no longer be used.

The amount of damage that constitutes unacceptable bridge failure is determined by a number of considerations, such as the bridge's (1) overall structure, (2) importance as a route for emergency vehicles following an earthquake, and (3) relationship to other structures that may or may not be affected during the same earthquake. These considerations are all part of the seismic retrofitting process, which involves a preliminary screening and priority ranking to identify vulnerable bridges; detailed engineering evaluations of specific bridge components and types; and the design of seismic retrofit measures for individual bridges.

Earthquakes Threaten Bridges in 31 States

Although widely believed to be unique to the western part of the country, earthquakes can and do occur throughout the United States. According to FHWA and earthquake engineering experts, 31 states contain areas where the potential ground shaking from earthquakes could be sufficient to damage highway bridges (see table 1 for a list of the states, and app. I, fig. I.1, for a map showing areas at risk from moderate- to high-intensity earthquakes).

Table 1: States With Bridges in Areas at Risk From High- to Moderate-Intensity Ground Shaking

15 states contain areas subject to high-intensity ground shaking	16 states contain areas subject to moderate-intensity ground shaking
Alaska	Connecticut
Arizona	Delaware
Arkansas	Georgia
California	Maine
Hawaii	Massachusetts
Idaho	Mississippi
Illinois	New Hampshire
Kentucky	New Jersey
Missouri	New Mexico
Montana	New York
Nevada	North Carolina
Tennessee	Oregon
Utah	Pennsylvania
Washington	Rhode Island
Wyoming	South Carolina
	Virginia

Note: There is no universally accepted definition of a "moderate-intensity" or "high-intensity" earthquake, in part because several different scales are used to measure earthquake intensity. The Richter scale, the most commonly used scale, measures the energy release of an earthquake at its center. Bridge engineers generally use another scale that measures the intensity of ground-shaking motions in percentages of gravity, or "g." Although we make references to Richter-scale measurements in this report, our definitions of moderate and high seismic-risk areas are based on the "g" number scale. App. I explains this scale and our definitions in greater detail.

Bridge damage from earthquakes is not limited to earthquakes of high intensity; moderate events could also cause significant bridge damage. In moderate-intensity earthquakes, loose soils such as landfill can intensify the shaking and cause bridge substructures and foundations to tilt, settle, slide, or even overturn. For example, the ground shaking from the Loma Prieta Earthquake near Santa Cruz, California, diminished with distance until it reached the soft muds under the Cypress Street Viaduct in Oakland, 60 miles away from the earthquake epicenter. The soft muds amplified the ground shaking by an estimated factor of 2.5 and probably caused the viaduct's collapse. Further, the eastern and central United States are particularly vulnerable to widespread ground shaking because seismic vibrations in the earth's crust travel for far greater distances in that region. For example, the New Madrid quakes of 1811-12 were felt throughout the eastern United States, ringing church bells in Boston and collapsing scaffolds in Washington, D.C., over 600 miles away.

The structural characteristics of a bridge also affect its vulnerability to earthquake damage. Historically, bridge damage has occurred when the bridge span or superstructure becomes unseated from its supporting elements. For example, nearly every bridge along the partially completed Cooper River highway was seriously damaged or destroyed in the 1964 earthquake in Alaska. The 1971 San Fernando earthquake in southern California damaged over 60 bridges. According to earthquake engineering experts, certain types of bridges, such as those with simply supported spans with narrow seatwidths,[3] are less able to resist earthquake forces and may be most vulnerable to damage or collapse during earthquakes. While the specific number and distribution of bridges with simply supported spans is unknown, according to GAO's consultant, up to 75 percent of the national bridge inventory may be of this type. (See app. II for a further discussion of this issue.)

Experts believe that earthquakes are likely to strike the eastern half of the country within the next 50 years. Research by the U. S. Geological Survey (USGS) in September 1990 estimates that there is a 40- to 60-percent chance of an earthquake of magnitude 6 or greater in the central or eastern United States within the next 30 years.[4] Also, there is a 40- to 63-percent probability of a magnitude-6 earthquake along the New Madrid fault within the next 15 years, and an 86- to 97-percent chance in the next 50 years, according to seismic experts.

Studies in the late 1980s conducted by various engineering experts and the Federal Emergency Management Agency (FEMA) indicate that if cities in the East and Central Mississippi Valley regions were to experience earthquakes comparable to those in the past, significant bridge damage would result. For example, these studies estimate that the damage from a 7.6-magnitude quake in St. Louis would reduce highway and bridge capacity by 30 to 45 percent. (See app. II for additional information.) The studies also point out that damage to key bridges, such as long-span structures crossing major rivers, would impede emergency response vehicles and disrupt regional and national commerce. The Loma Prieta Earthquake, for example, caused an estimated $1.8 billion in damage to the transportation system in the San Francisco Bay area. The quake also caused much disruption and hardship to individuals and

[3] Seatwidth refers to the width of an abutment (as shown in fig. II.1 of app. II) or other component of the bridge substructure that holds up the bridge span.

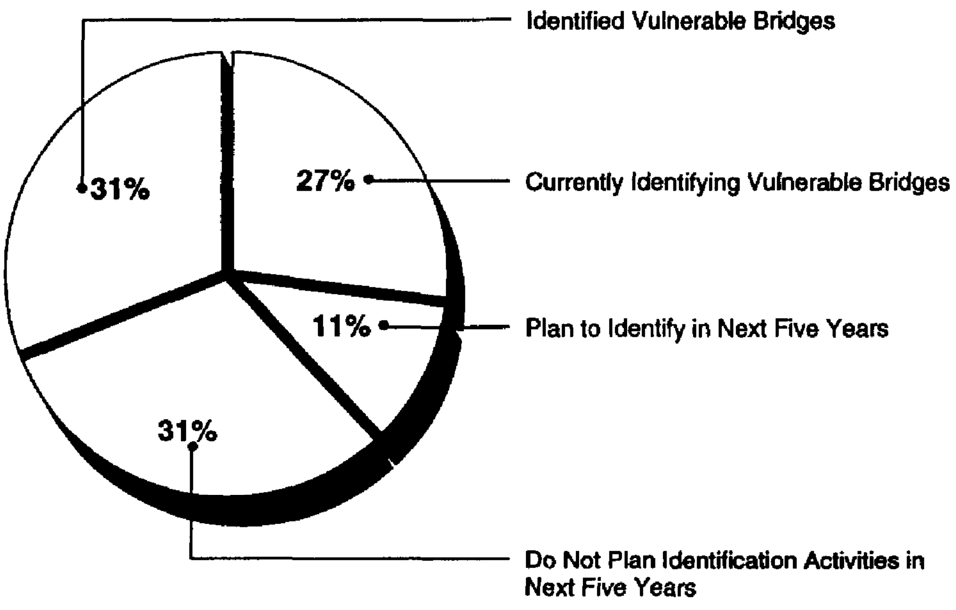
[4] Magnitude refers to earthquake size, as measured by the Richter scale. As a means of comparison, the Loma Prieta Earthquake, at a magnitude of 7.1, would be about 10 times stronger than a magnitude-6 earthquake.

businesses because the Bay Bridge—the major transportation link between San Francisco and Oakland—was closed for one month.

States Have Made Limited Progress in Identifying and Correcting Seismic-Related Bridge Deficiencies

Most bridge engineers from the 26 states contacted generally recognize the earthquake's potential to damage their highway bridges, but they have made limited progress in identifying and correcting seismic-related bridge deficiencies. Although FHWA encourages states with seismically active areas to identify the number and type of vulnerable bridges, 8 of the 26 states contacted advised us that they had no plans to identify (inventory) these bridges within the next 5 years. Of the remaining 18 states, 7 states advised us they were in the process of identifying vulnerable bridges, 3 states said they planned to do so within the next 5 years, and 8 states had already identified their vulnerable bridges. (See app. III for a state-by-state breakdown of progress.) Figure 1 shows the status of states' efforts to identify bridges vulnerable to earthquake damage, as of April 1991.

Figure 1: Status of 26 States Identifying Bridges Vulnerable to Earthquake Damage



Source: Data developed by GAO.

Identifying bridges vulnerable to earthquake damage is an essential first step in developing an effective seismic retrofit approach. Factors to consider when conducting a preliminary screening and priority ranking to identify vulnerable bridges involve the bridge's proximity to seismically active areas, design and structural condition, and importance as a vital transportation route. Identifying bridges most in need of seismic retrofit, such as bridges on critical "lifeline" routes, is particularly important, since these bridges must remain functional for emergency response after the earthquake.

Eight of the 26 states we contacted had performed a preliminary screening of seismically vulnerable bridges. For example, in May 1991 Washington State completed a preliminary screening and priority ranking that identified 914 bridges as potentially vulnerable to earthquake damage. In 1991, according to a Washington official, the state legislature approved $6.5 million to begin installation of hinge restrainers on 87 bridges,[5] and to perform a more detailed engineering analysis of 36 bridges with unique structural features. In 1991, Arizona performed a preliminary screening that identified 170 bridges along 5 highway routes as vulnerable to earthquake damage. Arizona subsequently has begun detailed engineering evaluations on 17 key bridges and completed retrofit design work on 1 bridge. Several states completed preliminary screening work through a review of bridge plans that required only limited on-site bridge inspections.

Progress in retrofitting bridges vulnerable to earthquake damage has been very limited. Of the eight states with completed inventories, four states had retrofitted, or were in the process of retrofitting, the bridges they considered vulnerable to earthquake damage. Retrofit work in 3 of the 4 states totaled only about 2 percent (36 of 2,280) of such bridges. The fourth state (California), however, has set time frames and has a policy to allocate funding to complete seismic work by 1995 on the 4,820 bridges it had identified as vulnerable as of October 1990. Of the remaining four states with completed inventories, two states had not yet performed any retrofit work and the other two states had performed seismic retrofit work in conjunction with other bridge rehabilitation work but not on bridges identified in their inventories as vulnerable to seismic damage. All of these states, however, told us that they plan retrofit work in the next 5 years on bridges identified as vulnerable to earthquake damage.

In addition, although six other states have not completed seismic bridge inventories, they have incorporated seismic retrofit work into some

[5] Hinge restrainers refer to cables or bars used to secure sections of bridge spans that could separate during an earthquake.

bridges when other bridge rehabilitation work was performed. Thus, in total, we found that 12 of the 26 states had performed some seismic retrofit work in the past 5 years.

Funds needed to seismically retrofit a bridge vary tremendously according to the type of work needed. Certain types of seismic retrofit, such as reinforcement of columns, can be costly. California estimates that it will cost about $143 million to strengthen single-column supports on 392 bridges. A less costly, and the most common, type of retrofit work being conducted in the states we surveyed was the installation of restrainers in bridge superstructures. Seismic experts consider this procedure cost-effective in minimizing earthquake damage to bridges. From 1971 to 1988, for example, the California Department of Transportation (CALTRANS) installed restrainers in 1,261 bridges at a cost of $54 million. According to a CALTRANS official, the number of bridges damaged during the Loma Prieta Earthquake could have been much higher if such restrainers had not already been installed on 200 bridges located in the earthquake-affected area. Eight of the 12 states that have performed retrofit work in the last 5 years have installed such restrainers.

Bridge officials in 12 of the 26 states contacted said that their states' seismic retrofit activities were hindered by the amount of funds available for all highway and bridge work. Further, before January 1990 states were prevented from using federal bridge (HBRRP) funds to perform seismic retrofit work as a sole work item; such work had to be performed in conjunction with other bridge rehabilitation work. However, FHWA changed the eligibility criteria for bridges in seismically active areas following the Loma Prieta Earthquake. This change so far has had a limited impact in the states surveyed. Only 5 of the 26 states we reviewed said that the change helped them address seismic deficiencies in bridges. Officials in 19 states said that the change had no effect, primarily because limited HBRRP funding was already committed to other bridge rehabilitation work or because the state was not far enough along with seismic safety activities to consider HBRRP as a funding source.

Two other factors have also impeded state progress in addressing seismic bridge concerns. Bridge engineers from states that either had not yet identified seismically vulnerable bridges or did not plan seismic retrofit work told us the primary reason for inaction was the perception that the state was at low seismic risk. Bridge engineers also said they had difficulty interpreting existing seismic design specifications for new bridge construction and needed additional technical information on seismic retrofit techniques. For example, bridge officials from 13 of the

26 states expressed difficulties understanding various sections of AASHTO's "Guide Specification for the Seismic Design of Highway Bridges," including those on bridge foundations and the effects of soils on bridge design. Several states also reported that their progress in performing certain types of retrofit work, such as work on bridge columns and foundations, has been impeded by limited information and research on such procedures.

Further FHWA Actions Would Help States Address Bridge Seismic Safety

FHWA has taken steps to address bridge seismic safety by providing training and sponsoring research on seismic design and retrofit techniques and by encouraging states in earthquake-threatened areas to identify bridges vulnerable to seismic forces. However, state bridge officials and earthquake engineering experts believe that FHWA needs to do more to facilitate retrofit efforts by expanding training opportunities available to state and FHWA bridge engineers and by acting as a focal point (clearinghouse) for the dissemination of bridge-related seismic information. Additional FHWA actions are also needed to ensure that states identify seismically vulnerable bridges.

States Express Need for Additional Training and Information on Seismic Research

FHWA recognized the need to improve states' seismic bridge design capability when it developed a training course in June 1989 entitled "Seismic Design of Highway Bridges." The course is structured to provide state bridge engineers, as well as FHWA engineers in need of such training, with a 3-day introduction and overview of seismic design, plus 1 day devoted to retrofit procedures. Before Loma Prieta, interest in the course was minimal; afterward, with FHWA encouragement, 25 states have sponsored the course for their engineers as of July 1991, according to an FHWA official. In addition, FHWA is developing a training course on the seismic design of bridge foundations.

However, most of the state and FHWA bridge engineers, as well as earthquake engineering experts we contacted, told us that state bridge engineers need training in bridge seismic design and retrofit techniques beyond that currently offered by FHWA. Specifically, they said that training is needed in areas such as low-cost seismic retrofit techniques, computer software for seismic design, and retrofit techniques for bridges on soft soils that can liquefy when strongly vibrated. In addition, almost all FHWA division bridge engineers (22 of 26 division offices) contacted said that additional seismic design training would be useful to FHWA bridge engineers in assisting states with seismic safety activities. According to GAO's consultant, bridge engineers generally have little experience designing bridges to resist seismic loading and need additional training in seismic retrofit beyond the 1-day segment offered in FHWA's introductory course.

State and FHWA field bridge engineers also expressed the need for a central source to obtain seismic-related bridge information. Most of the engineers we spoke with said that they needed additional information on seismic research. These engineers believe that FHWA should act as a focal point for the dissemination of such information, and this could lead to the more timely deployment of recent research. Since the Loma Prieta Earthquake, a number of states, federal agencies, and university-based earthquake engineering research centers have begun research relating to bridge seismic safety. (See app. IV for further discussion of this issue.) Bridge engineers from several states said that a clearinghouse would help states avoid duplication of research performed by states or federal agencies. Earthquake engineering experts also told us that such a clearinghouse would allow FHWA to act as a focal point for future federally sponsored research concerning bridge seismic safety.

States Not Required to Identify Bridges Vulnerable to Earthquakes

FHWA has not required states to inventory bridges located in seismically active areas, although it has required states to inventory bridges susceptible to damage from another natural hazard—flooding. FHWA's approach has been to encourage, rather than require, states to inventory seismically vulnerable bridges. The agency has taken this approach, FHWA bridge division officials said, because, unlike flooding, the threat of earthquake damage is not considered a nationwide problem and the degree of seismic risk varies significantly among states prone to earthquakes. However, as discussed previously, 18 of the 26 seismically active states we reviewed had not completed an inventory of such bridges as of April 1991. While 10 of the 18 states were conducting an inventory or planned to conduct one within the next 5 years, the remaining 8 states said they have no plans to do so.

FHWA has also not required states to provide seismic-related information on earthquake-threatened bridges for inclusion in the National Bridge Inventory (NBI), according to FHWA officials. Under the National Bridge Inspection Program, states are required to inspect the condition of their bridges and submit the results to FHWA to include in the NBI. The NBI is the data base used by FHWA to record the structural condition of the nation's bridges, which is periodically reported to the Congress.

FHWA division bridge engineers told us they could better assist states in developing an approach to seismic retrofit and help them assess state progress in correcting seismic-related bridge deficiencies if they had basic information on vulnerable bridges. Nineteen of 26 FHWA division bridge engineers, and 15 of 22 state bridge engineers who expressed an opinion, supported adding such data elements to the NBI. FHWA headquarter's officials in the Bridge Division, however, said there was no need to add this information to the NBI. These officials noted that states are primarily responsible for planning and designing federally funded bridge projects; thus the information need is at the state level. While we recognize the need for this information at the state level, we believe the information is also needed at the federal level to obtain a nationwide perspective on the problem of seismically vulnerable bridges.

Further, the NBI currently consists of 116 data elements, with 23 of these elements used in determining whether a bridge is deficient and eligible for federal funding. FHWA Bridge Division officials are concerned that adding seismic data elements to the NBI could increase the number of bridges considered deficient in states with high to moderate seismic-risk areas, thus affecting the apportionment of federal bridge funds provided to all states. We are not suggesting that the inclusion of data elements related to bridge seismic vulnerability alter the apportionment of bridge funds, as we consider such an action premature at this time. Rather, we believe that basic, state-comparable information is needed to gauge the extent to which the nation's bridges are vulnerable to earthquakes and provide a benchmark for determining progress in retrofitting critical bridges.

Conclusions

Because a number of states have not identified bridges at risk from earthquakes, information on the number and types of bridges needing retrofit is essentially unknown. What is known from California's Loma Prieta Earthquake is that the resulting bridge damage can be extraordinarily costly in terms of lives lost and bridge repair and replacement costs, which are now expected to reach $1 billion in federal aid.

An essential first step in determining the need to retrofit seismically vulnerable bridges is to ensure that states in seismically active areas have identified the number and types of vulnerable bridges. However, a number of states we contacted in areas threatened by earthquakes either have not yet done so or do not plan to do so between 1991 and 1996.

Progress by states in addressing seismic-related bridge deficiencies has been limited because (1) funds for seismic retrofit compete with other highway or bridge projects aimed at correcting existing deficiencies, (2) some states believe that bridges are at low risk to earthquake damage, and (3) more information is needed on seismic design and retrofit techniques.

To further assist states in overcoming these impediments, we believe FHWA should ensure that states are fully aware how vulnerable their bridges are to earthquake damage so that such risks can be assessed along with other factors that affect priorities for bridge rehabilitation. Such assessments by states should be designed to provide comparable data on the vulnerability of the nation's bridges. The assessments should also allow FHWA, in the long term, to assess whether states' progress in correcting vulnerable bridges is adequate to ensure the safety of highway users as well as to protect the nation's investment in the federal-aid highway system. States could also make greater progress in correcting seismic-related bridge deficiencies if FHWA provided bridge engineers in states and FHWA field offices with additional training and access to the latest research on seismic design and retrofit techniques.

Recommendations

We recommend that the Secretary of Transportation direct the Administrator, FHWA, to (1) require states in areas of moderate to high seismic risk to identify bridges vulnerable to earthquake damage in conjunction with their routine bridge inspections and report this information on seismically vulnerable bridges to FHWA for inclusion in the National Bridge Inventory, (2) expand the range of seismic-related training, and (3) consolidate and disseminate bridge-related seismic information and research to states.

We performed our work with 26 states and appropriate FHWA and other federal agencies from September 1990 to August 1991 in accordance with generally accepted government auditing standards. To assist us in evaluating technical issues associated with our review, we retained an earthquake engineering consultant, Dr. Ian Buckle, Deputy Director, National Center for Earthquake Engineering Research, State University of New York at Buffalo. (Further details on our objectives, scope, and methodology are contained in app. V.)

We discussed the information in this report with responsible FHWA officials, who agreed with our presentation of the facts. In general, these officials acknowledged the need for additional seismic training and information exchange. FHWA's primary disagreement concerned the inclusion of seismic vulnerability data elements in the NBI, which they feared could result in changes in how federal bridge funds are apportioned. We do not necessarily draw this inference, as the majority of NBI data elements are not used to apportion federal bridge funds. Moreover, we believe that basic, comparable state information is needed to determine the seismic vulnerability of the nation's bridges. We incorporated FHWA's comments where appropriate. However, as agreed with your office, we did not obtain written agency comments.

We will send copies of this report to the Secretary of Transportation; the Administrator, FHWA; and participating states. Copies will be sent to other interested parties upon request. This report was performed under the direction of Kenneth M. Mead, Director, Transportation Issues, who may be reached at (202) 275-1000. Major contributors to this report are listed in app. VI.

J. Dexter Peach
Assistant Comptroller General

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Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
CALTRANS	California Department of Transportation
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GAO	General Accounting Office
HBRRP	Highway Bridge Replacement and Rehabilitation Program
NBI	National Bridge Inventory
NIST	National Institute of Standards and Technology
SPC	Seismic Performance Categories
USGS	U. S. Geological Survey

Bridges in 31 States Are at Risk From Damage by Earthquakes

This appendix explains how seismologists and engineers measure seismic risk for bridges and how these hazards are translated into design requirements.

Different scales are used to measure earthquake hazards. The Richter scale measures the energy release of an earthquake at its epicenter,[1] while ground acceleration measures the intensity of the ground-shaking motions as a fraction of gravity, or "g". The g number is more meaningful than Richter-scale measurements for designing structures. For example, a bridge in an area with an acceleration coefficient of 1g may experience earthquake- induced shaking equal to its entire weight acting as a horizontal force upon the bridge structure. This occurs because a bridge can amplify the ground acceleration.

The American Association of State Highway and Transportation Officials' Standard Specifications for Highway Bridges require bridge designers to use acceleration coefficients to determine the type and extent of seismic design required for a bridge to resist the predicted ground shaking in a seismically active area. The specifications place bridges that are vulnerable to earthquake damage in one of four Seismic Performance Categories (SPC): A, B, C, or D. According to the Standard Specifications:

- Bridges in areas with an acceleration coefficient less than or equal to .09g (SPC A) do not need detailed seismic analysis other than checking for minimum connection requirements between the bridge superstructure and its supports.
- Bridges in areas with an acceleration coefficient less than or equal to .19g and greater than .09g (SPC B) require seismic analysis and must satisfy minimum design requirements for the columns, foundations, and connections between these bridge components and the superstructure.
- Bridges in areas with an acceleration coefficient above .19g (SPCs C and D) require more rigorous seismic analysis than bridges in category B, and detail designs of the columns, foundations, and connections must be carried out.

We termed states with bridges in areas categorized as SPC A to be at risk from low-intensity ground shaking; 19 states and the District of Columbia fall into this category. We termed states with bridges in areas categorized as SPC B to be at risk from moderate-intensity ground

[1] Epicenter refers to the point on the earth's surface vertically above the subsurface location where an earthquake begins.

shaking; 16 states fall into this category. We termed states with bridges in areas categorized as SPCs C and D to be at risk from high-intensity ground shaking; 15 states fall into this category. See table I.1 for a list of states.

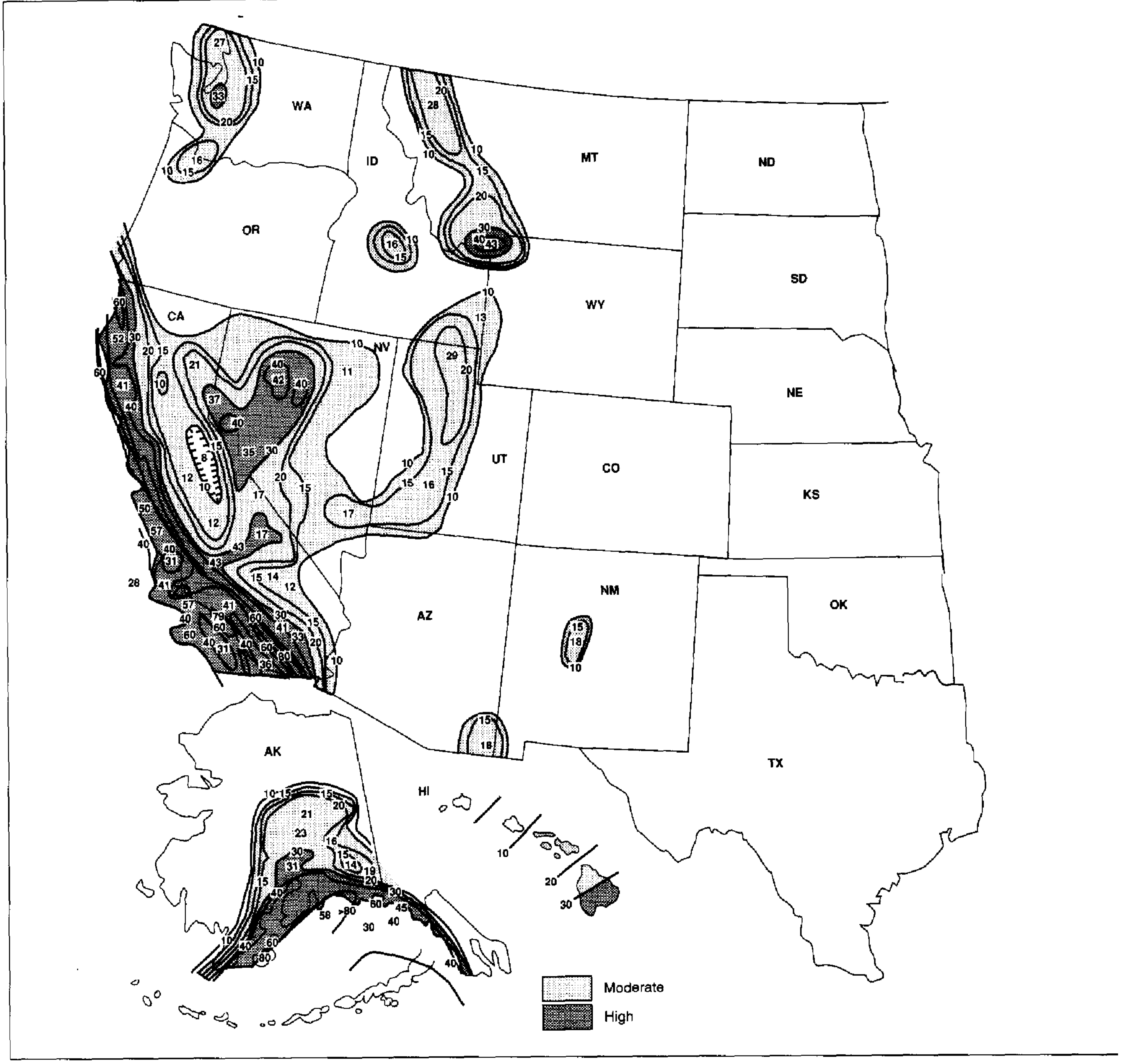
Table I.1: States With Bridges in Areas at Risk From Earthquake-Induced Ground Shaking

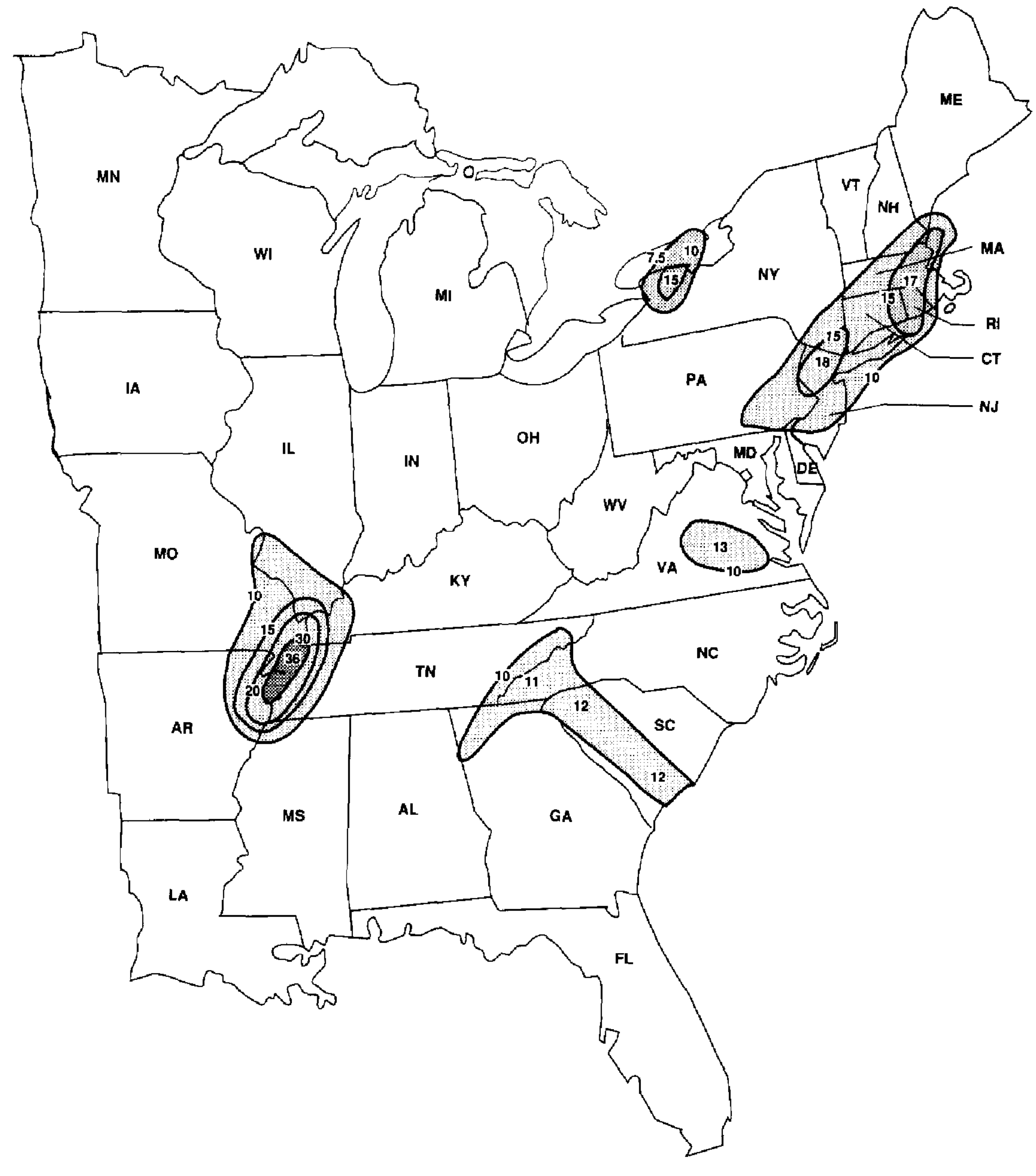
Low-intensity ground shaking	Moderate-intensity ground shaking	High-intensity ground shaking
Alabama	Connecticut	Alaska
Colorado	Delaware	Arizona
District of Columbia	Georgia	Arkansas
Florida	Maine	California
Indiana	Massachusetts	Hawaii
Iowa	Mississippi	Idaho
Kansas	New Hampshire	Illinois
Louisiana	New Jersey	Kentucky
Maryland	New Mexico	Missouri
Michigan	New York	Montana
Minnesota	North Carolina	Nevada
Nebraska	Oregon	Tennessee
North Dakota	Pennsylvania	Utah
Ohio	Rhode Island	Washington
Oklahoma	South Carolina	Wyoming
South Dakota	Virginia	
Texas		
Vermont		
West Virginia		
Wisconsin		

To assist engineers in designing structures to resist earthquake forces, the U.S. Geological Survey (USGS) has developed national maps of areas that are subject to ground shaking of various intensities, according to a USGS official. Acceleration coefficients may range widely within a state or be fairly consistent across the state. For example, acceleration coefficients in California range from .05g to over .80g, while North Dakota ranges only between .01g and .025g.[2] Figure I.1 shows areas of those states with an acceleration coefficient equal to or above .09g.

[2] The USGS maps estimate that if an earthquake occurs, there is a 90 percent chance within the next 50 years that the ground shaking will be equal to or less than the levels shown on the map. Stated another way, there is only a 10 percent chance that shaking from an earthquake will be more intense than the levels shown on the map.

Figure I.1: Bridges in 31 States Are at Risk From Damage by Earthquakes of High- to Moderate-Intensity





Source: Prepared by GAO from a map developed by the U.S. Geological Survey for the 1988 edition of NEHRP Recommended Provisions for the Development of Seismic Regulations for New Buildings.

Bridge Vulnerability to Earthquakes

In order to assess the vulnerability of bridges to earthquake damage, we retained an earthquake engineering consultant. The consultant, Dr. Ian G. Buckle, is Deputy Director of the National Center for Earthquake Engineering Research at the State University of New York at Buffalo. He is a principal author of the 1987 Federal Highway Administration (FHWA) publication, Seismic Design and Retrofit Manual for Highway Bridges, and has authored several books and numerous articles on earthquake engineering and bridge seismic design.

We asked the consultant to (1) identify characteristics of bridges that make them vulnerable to earthquake damage, (2) summarize recent studies estimating the potential damage to highways and bridges in selected cities, and (3) estimate bridge damage from a moderate- and high-intensity earthquake occurring in areas of seismic risk in an eastern and a central state. Below is a summary of his work.

Highway Bridges Are Vulnerable to Earthquake Damage Due to Site Hazards and Bridge Type

The vulnerability of any given bridge to earthquake damage is, in large part, a function of the seismic conditions at the bridge site and the type of bridge structure. Historically, bridges have proven to be vulnerable to earthquakes, and in some cases they have been totally destroyed as bridge superstructures are unseated from their supporting elements. The risk earthquakes pose for bridges is evidenced by the fact that nearly every bridge along the partially completed Cooper River highway was seriously damaged or destroyed in the 1964 earthquake in Alaska. The 1971 San Fernando Earthquake in southern California damaged over 60 bridges. The 1989 Loma Prieta Earthquake damaged about 97 bridges in or near the San Francisco Bay area of northern California.

Soft Soils Can Intensify Bridge Damage From Earthquakes

Soft soil types found throughout the United States can intensify the damage to bridges during earthquakes. First, water-saturated sands and silts can liquefy when strongly vibrated, forcing a layer of sand or water to the surface while the soil settles. Such liquefaction can cause sudden loss of support to the foundations of a bridge; bridge damage due to liquefaction was observed in earthquakes in Charleston (1886), Alaska (1964), and San Francisco (1989). Second, loose soils like landfill or the type found along a river can have an intensifying effect depending on the size of the earthquake. In large earthquakes such soils can reduce the amount of ground shaking at the surface. In low- to moderate-intensity earthquakes, however, these soils can intensify the ground shaking and result in more destructive surface shaking over a wider surface area. This amplified shaking can cause bridge substructures and foundations to tilt, settle, slide, or even overturn.

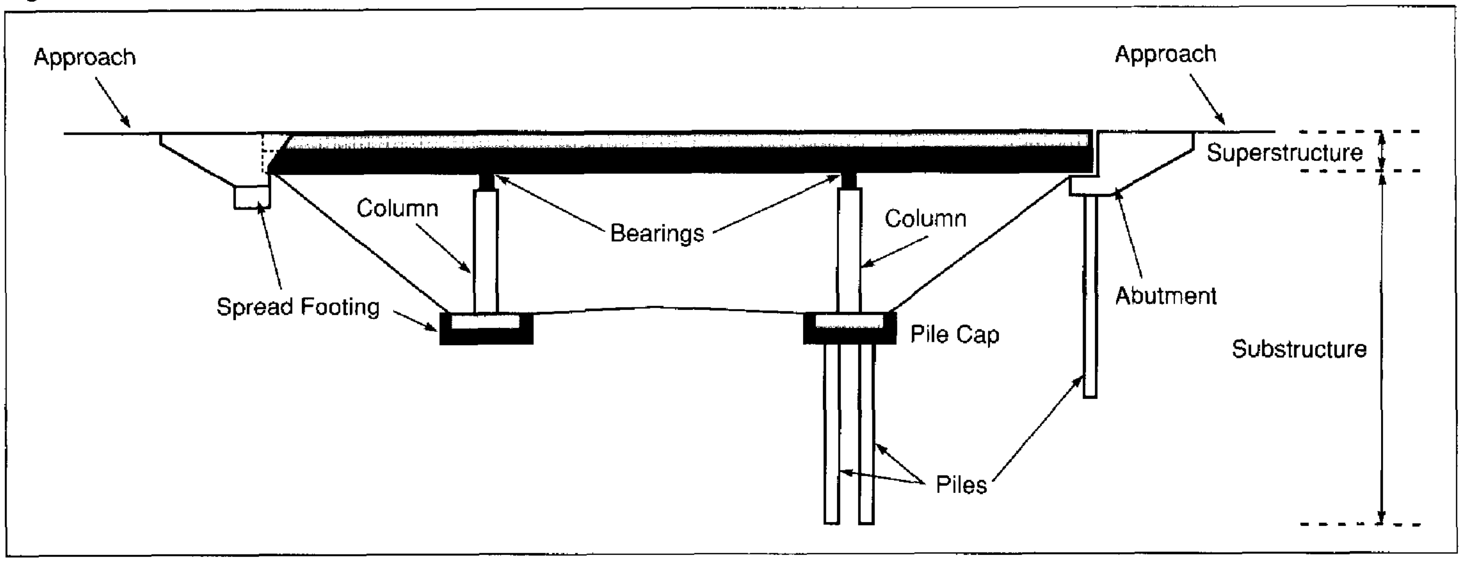
For example, the ground shaking from the Loma Prieta Earthquake near Santa Cruz, California, diminished with distance until reaching the soft muds under the Cypress Street Viaduct in Oakland, 60 miles away from the earthquake epicenter; there, the soft muds amplified the ground shaking by an estimated factor of about 2.5 and probably caused the viaduct's collapse. Further, the eastern and central United States are particularly vulnerable to such widespread ground shaking because the bedrock (solid rock underlying soils) in the East is not split (fractured) by active earthquake faults. Earthquakes are therefore felt over wide regions. For example, the New Madrid quakes of 1811-12 were felt throughout the eastern United States, ringing churchbells in Boston and collapsing scaffolds in Washington, D.C., over 600 miles away.

Certain Types of Bridge Structures Are More Vulnerable

Bridge types vary considerably across the nation, but the most common types all require substructures to support the individual spans. The substructures will usually be columns or piers made from concrete or masonry, which in turn are supported by spread or pile footings. All bridges regardless of type require abutments to support the end spans.[1] Fig. II.1 shows common bridge components.

[1] Abutments, part of the bridge substructure, act to support the end span of the bridge superstructure at the approach to that span.

Figure II.1: Common Bridge Components

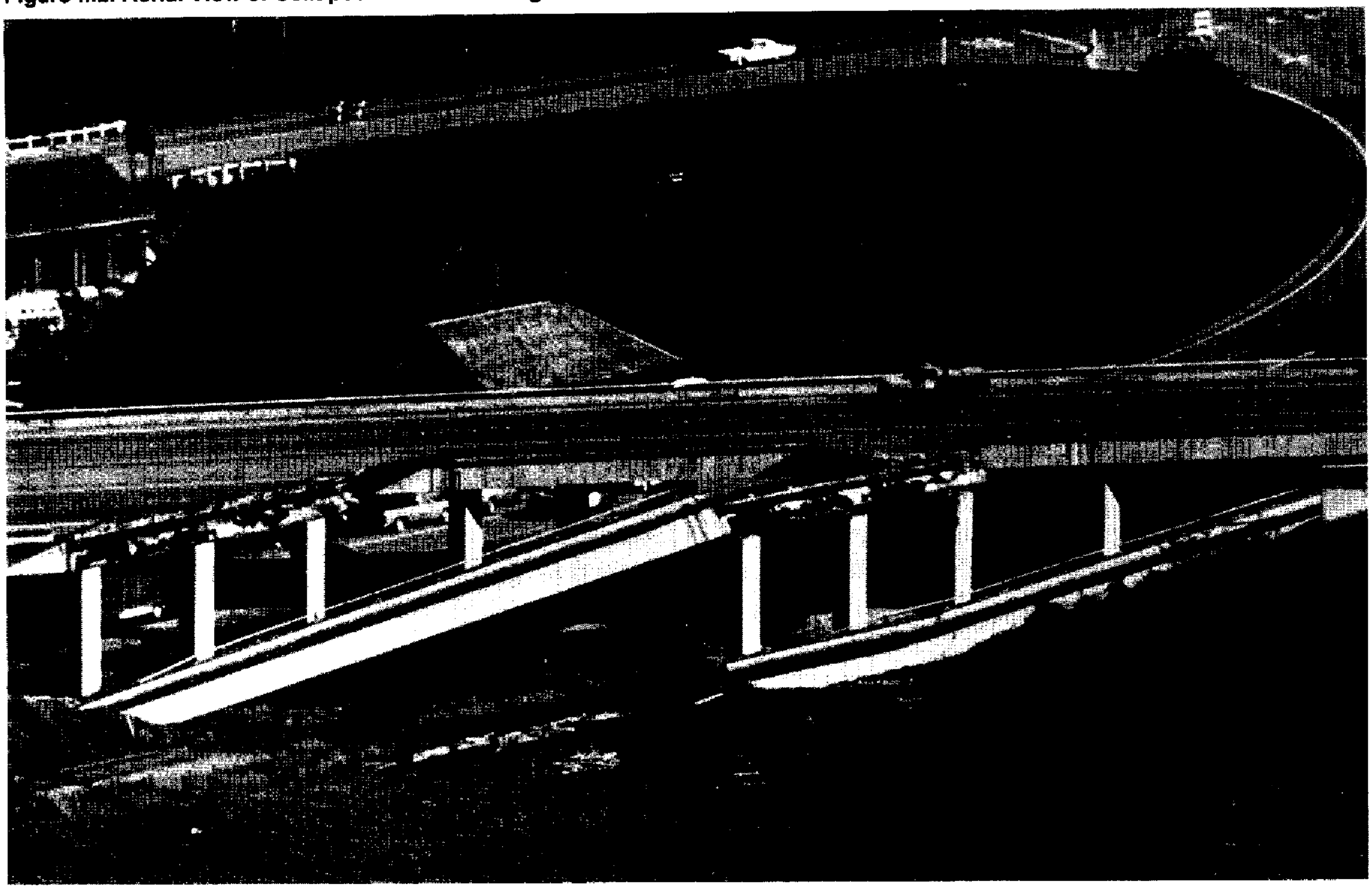


Earthquake damage to bridge structures may occur in the superstructure, the substructure, or the approaches. Failures in the connections between various bridge components are the most common type of damage and may take several forms. Connection failures include the failure of bearings,[2] which connect the superstructure to the substructure, as well as failures that occur within the substructure. Examples of substructure connection failures include columns, which are dislodged from the footings or pile caps. Connection failures were identified as the principal reason for the collapse of the Cypress Street Viaduct and the link spans of the San Francisco-Oakland Bay Bridge during the Loma Prieta Earthquake.

Connection failures also occurred on the Fields Landing Overhead during a 7.0 Richter-scale magnitude earthquake in November 1980 near Eureka, California. As figure II.2 shows, major damage was incurred on this structure when two of four bridge spans collapsed--seriously injuring six people.

[2] Bearings are mechanical devices that permit thermal and other movements to occur between various bridge components, such as the bridge span and supporting columns. Expansion bearings, such as those made of rubber, allow movement between the girder and supports; fixed bearings allow no movement between the girder and the supports.

Figure II.2: Aerial View of Collapsed Fields Landing Overhead

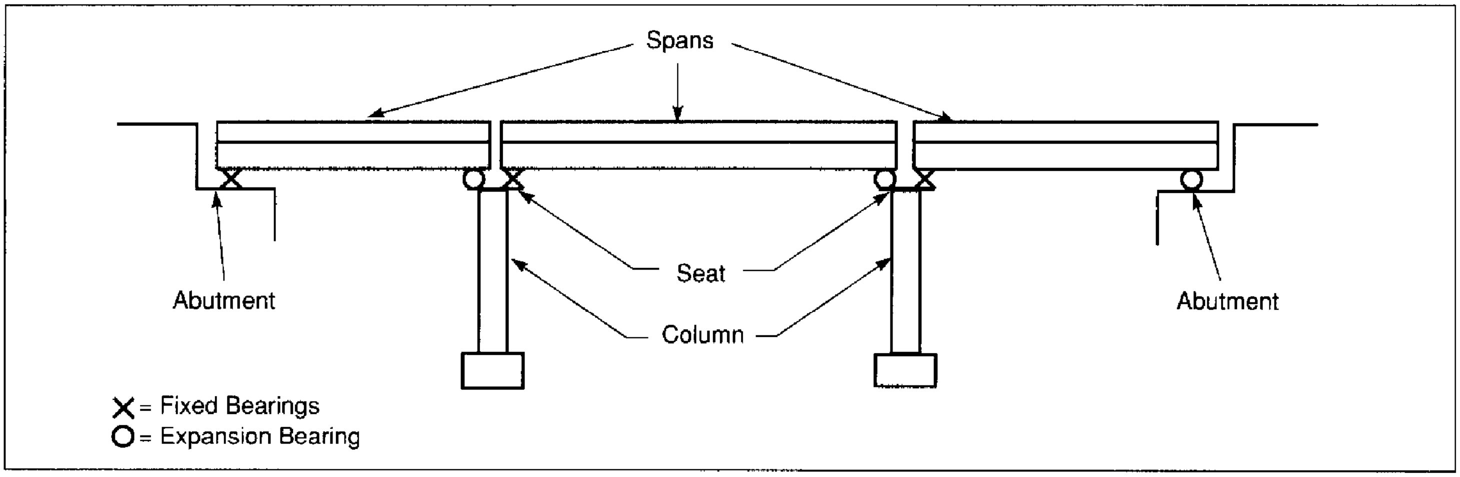


Source: Neil F. Gilchrist, Times Standard-Eureka, California.

Certain types of bridge structures are less resistant to earthquake forces. The manner in which the superstructure is connected to the substructure is of particular importance in evaluating seismic vulnerability. The most common type of bridge vulnerable to earthquake shaking is one with simply supported spans with deficient bearings and inadequate seatwidths[3] (see fig. II.3).

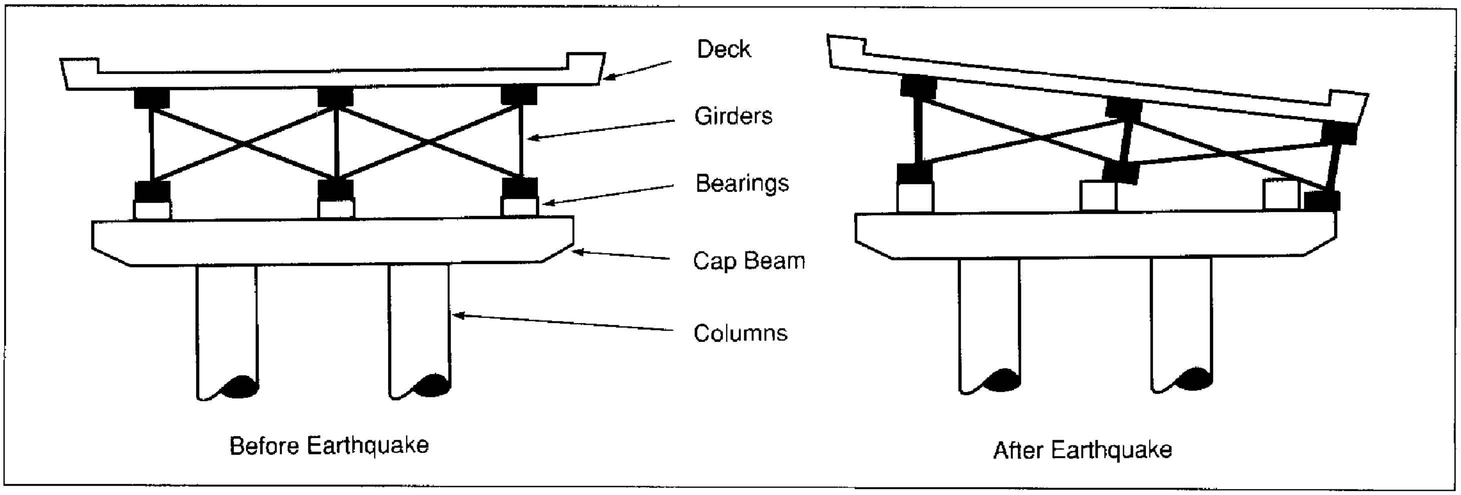
[3] Seatwidth refers to the width of an abutment or other component of the bridge substructure which holds up the bridge span. Earthquake-induced ground shaking can cause bridge spans to slip off their supports if seatwidths are too narrow.

Figure II.3: Bridge With Simply Supported Spans



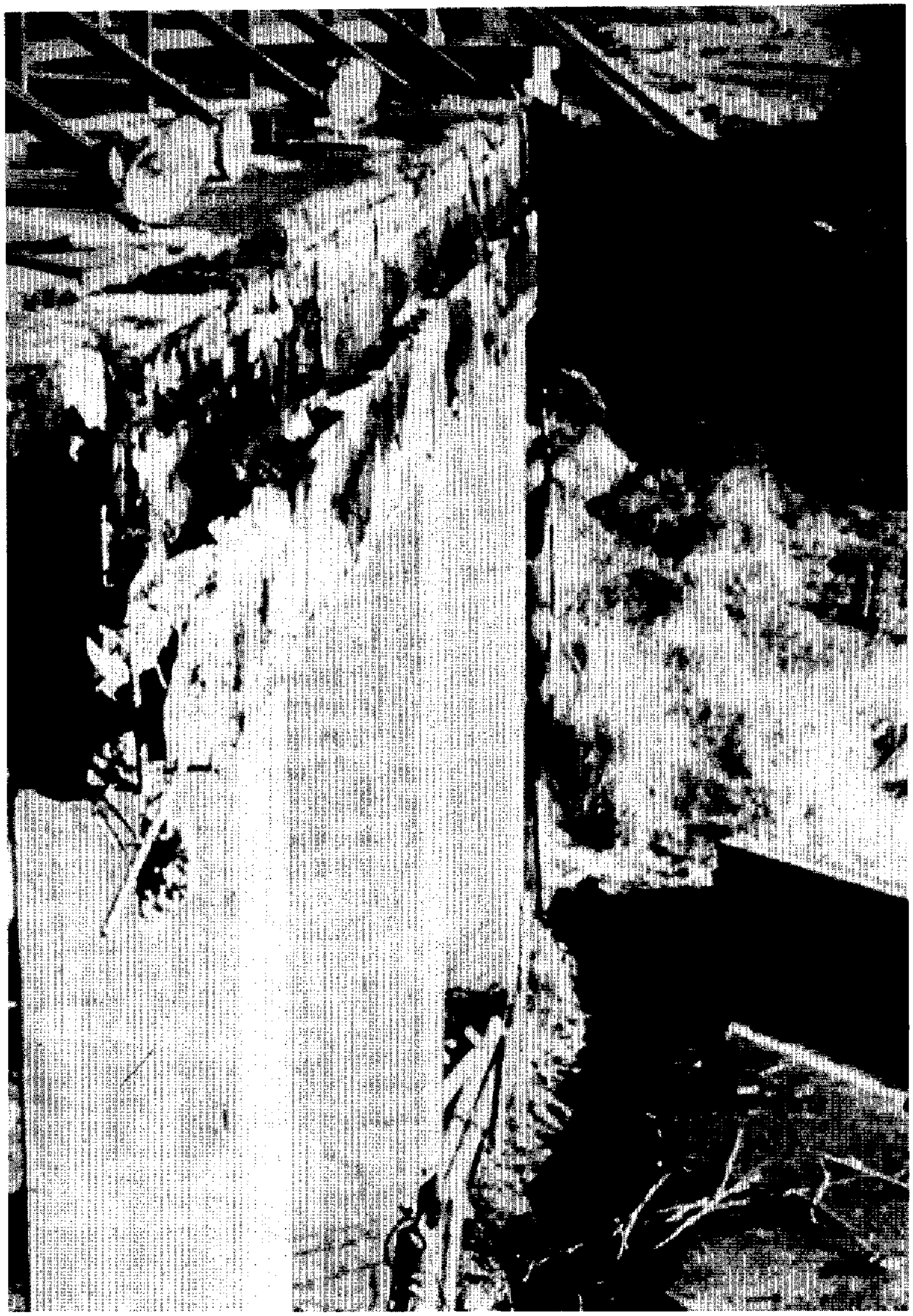
A common reason for damage in simply supported bridges is inadequate seatwidths of the girder supports. During shaking, large relative movements between the girder and the support can unseat the girder, which could damage or cause the collapse of one or more bridge spans (see fig. II.4).

Figure II.4: Unseating of Bridge Spans That Are Simply Supported During Earthquake Movements



The Fields Landing Overhead collapse near Eureka, California was caused principally by the inadequate length of the seatwidths supporting the bearings which resulted in the bridge spans slipping off their supports (see fig. II.5).

Figure II.5: Collapse of Bridge Spans on the Fields Landing Overhead



Source: Dr. Roy A. Imbsen, P.E., Imbsen and Associates.

The specific number and distribution of bridges with simply supported spans and insufficient seatwidths are currently unknown because data from the FHWA's National Bridge Inventory do not contain girder seat details. The percentage of bridges in this category, however, is probably considerable, especially for eastern and central states. For example, a New York State Department of Transportation survey of bridges in four counties found 71 percent of the bridges to be simply supported spans.

The Bridge Engineer of the Missouri State Department of Transportation estimated that about 95 percent of the bridges on the state system did not satisfy the (AASHTO) minimum seatwidth requirement. A survey of bridges in the county around Memphis, Tennessee, found 85 percent were simple span bridges.

Federal and State Studies Predict That Bridges Are Vulnerable to Earthquake Damage

The collapse or closure of a bridge because of an earthquake can have severe consequences. Bridge collapses, as the Loma Prieta Earthquake demonstrated, can threaten the safety of highway users. In addition, bridges that suffer damage but remain closed for extended periods can prevent vital emergency services from going through or impede the economic recovery of affected communities. Loss studies or damage scenarios are used to estimate how earthquakes of different magnitudes may affect a city, including the potential damage to bridges. Table II.1 summarizes studies funded by the Federal Emergency Management Agency (FEMA) and the State of California to estimate potential damage to highways and bridges should a major earthquake occur near one of the following cities: St. Louis, Memphis, Los Angeles, Boston, and Charleston.

Table II.1: Summary of Bridge Damage Estimates for Five Cities

	Earthquake scenario		Damage to highways and bridges	
City	Magnitude	Probability of event	Percent reduction in highway/bridge capacity	Potential effect on highways
St. Louis, Missouri[a]	7.6[b]	20-30 percent by Yr 2035	30-45	Highway damage will disrupt regional and national commerce. For a 7.6 magnitude earthquake, 55-70 percent of the key river crossing highways will be functional.
	8.6	2.7-4 percent by 2035	50-75	For a 8.6 magnitude earthquake, only 25-50 percent of the key river crossing highways will be functional.
Memphis, Tennessee	7.6	Not available	Not available	Estimated damage will be extensive and traffic will be seriously restricted. Access into the city will probably be interrupted on at least half the major routes.
	8.6	Not available	Not available	Very few major highway bridges will be available for use, severely restricting mobility throughout the city. At least one of the two Mississippi River crossings will probably be damaged. All but 2 or 3 of the 11 access routes into the city will probably be closed.
Los Angeles, California[c]	7.0	Not available	Not available	Liquefaction on Terminal Island will damage approaches to 3 bridges. Sixteen major routes will be blocked/partially closed due to damaged bridges and broken pavement. Gigantic traffic jams will be present and hundreds of vehicles will probably be abandoned. Roads will not be cleared for 72 hours although limited emergency traffic use may be restored in about 24 hours.
Metropolitan Boston Area, Massachusetts[d]	6.25	Not available	Not available	Significant portions of the Boston area are on poor soils, and damage to highways in these areas is expected to be greatest. Also, damage may be underestimated because the study may not have adequately considered bridges' condition.
Charleston, S. Carolina[e]	MMI VII[f]	65 percent every 100 years	16	Traffic along most primary routes could be significantly disrupted. While alternative routes will probably be available, considerable travel delay and traffic congestion will result for at least 2 days as routes are being cleared.
	MMI IX	Probability uncertain	37	Because of the potential bridge damage, extensive rerouting, and streets in the older urban areas blocked by debris from buildings, fallen wires, and pavement damage, the traffic environment will be chaotic.

[a]"An Assessment of Damage and Casualties for Six Cities in the Central United States Resulting from Earthquakes in the New Madrid Seismic Zone," Federal Emergency Management Agency, Central United States Earthquake Preparedness Project, October 1985, pp. 3-11 to 3-13.

[b]Unless otherwise indicated, magnitude refers to the energy release of the earthquake as measured by the Richter scale.

[c]"Planning Scenario for a Magnitude Earthquake on the Newport-Inglewood Fault Zone," California Department of Conservation, Division of Mines and Geology, Tousson R. Toppozada, John H. Bennett, Glenn Borchardt, Richard Saul, and James F. Davis, 1988.

[d]"Metropolitan Boston Area Earthquake Loss Study: Loss Analysis Committee Report and Recommen-

dations," Robert J. Boulay, Director, Massachusetts Civil Defense Agency, February 1990.

[e]"An Earthquake Vulnerability Analysis of the Charleston, South Carolina Area," Maurice R. Harlan, P.E., and Charles Lindbergh, P.D., P.E., The Citadel, Department of Civil Engineering, July 1988, pp. 7-23 to 7-25.

[f]Magnitude refers to the energy release of an earthquake as measured by the Modified Mercalli Intensity (MMI) scale. The scale identifies twelve categories of ground motion intensity from I (not felt) to XII (nearly total damage).

Two Bridge Damage Scenarios

In order to estimate the potential damage to the bridges found most often in the eastern and central states, our consultant developed bridge damage scenarios to assess the impact of moderate and major earthquakes on bridges in New York City and in Memphis, Tennessee, in the New Madrid area in the Central Mississippi Valley region. Table II.2 summarizes these two scenarios, and is followed by the assumptions made.

Table II.2: Consultant Estimates for Bridge Damage Due to an Earthquake in Two Cities

	New York City		Memphis	
Approximate number of bridges:				
In metropolitan area	2,000		820	
With simple spans	1,500		615	
Earthquake	Moderate	Large	Moderate	Large
A = acceleration coefficient	A = .15g	A = .38g	A = .30g	A = .60g
Soil type I[a]	N[b]	N	N	Y[c]
Soil type II[d]	N	Y	N	Y
Soil type III[e]	N	Y	Y	Y
Soil type IV[f]	N	Y	Y	Y
Approximate number of bridges with unseated girders	0	1,125	300	615
Percentage of bridges with unseated girders relative to metro area	0	56	37	75

[a]Soil Type I (referred to in Appendix A of AASHTO's Standard Specification for the Design of Highway Bridges) has site coefficient, S = 1.0.

[b]N=No spans unseated.

[c]Y=All simple spans unseated.

[d]Soil Type II has site coefficient, S = 1.2.

[e]Soil Type III has site coefficient, S = 1.5.

[f]Soil Type IV has a site coefficient, S = 2.0.

The following assumptions were made in preparing these scenarios:[4]

1. Inadequate seatwidths can be used as a measure of bridge vulnerability.

2. Seventy-five percent of all bridges in the two regions have simple spans and the average seatwidth is 6 inches.

3. Bridges are uniformly distributed across all soil types.

4. The 5 percent damped elastic response spectrum from the AASHTO Standard Specifications may be used to calculate the superstructure displacements.

5. The average effective bridge period is 1.0 second and single-mode response dominates.

6. The seismic hazard is described by peak ground accelerations given in the USGS seismic hazard map (see app. I) and the soil site coefficients as given in AASHTO.

7. The return period for a moderate earthquake is approximately 500 years, and 2,500 years for a large earthquake.

The consultant used AASHTO formulas for superstructure displacements as follows:

$$Sa = \frac{1.2AS}{T\ 2/3} \quad \text{and} \quad Sd = \frac{SaT^2}{4\pi^2}$$

where Sa is spectral accelerations and Sd is spectral displacement and A = peak ground acceleration, S = soil site coefficient, and T = bridge period of 1.0 second, and pi=3.1416. Substitution gives Sd = 0.0304 AS.

[4] References to AASHTO in assumptions 4 through 6, and in subsequent formulas, refer to Appendix A of AASHTO's Standard Specification for the Design of Highway Bridges (formerly AASHTO's 1983 Guide Specification for Seismic Design of Highway Bridges).

Status of 26 States Identifying and Correcting Seismic-Related Bridge Deficiencies

We contacted 26 states and asked them about any activities under way to identify and correct seismic-related bridge deficiencies. Concerning identification activities, 8 states said they had completed an inventory of seismically vulnerable bridges within the last five years;[1] 10 states were either currently performing such an inventory or planned one within 5 years; and 8 states did not plan to conduct such an inventory in the next 5 years (see table III.1). Concerning retrofit work done to correct seismic-related bridge deficiencies, 12 states said they had done some retrofit work within the last 5 years; 10 states had some retrofit work under way or planned within 5 years; and 4 states do not plan any retrofit work during the next 5 years (see table III.2).

[1] Seven of the 15 states with areas categorized as high seismic activity, and 1 of the 16 states with moderate seismic activity, had completed an inventory of seismically vulnerable bridges.

Table III.1: Status of 26 States Identifying Bridges With Seismic-Related Deficiencies

High seismic-risk area	Inventory completed	Inventory in progress or planned	Inventory not planned
California	X		
Illinois	X		
Kentucky	X		
Missouri	X		
Nevada	X		
Washington	X		
Wyoming	X		
Alaska		X	
Arizona		X	
Idaho		X	
Hawaii		X	
Tennessee		X	
Arkansas			X
Montana			X
Utah			X
Moderate seismic-risk area[b]			
Connecticut	X		
Massachusetts		X	
New Jersey		X	
New York		X	
North Carolina		X	
Oregon		X	
Delaware			X
New Mexico			X
Rhode Island			X
South Carolina			X
Virginia			X
Total	**8**	**10**	**8**

[a]State includes areas where acceleration coefficient is greater than .19g.

[b]State includes areas where the acceleration coefficient is greater than .09g and equal to or less than .19g.

Table III.2: Status of 26 States Completing or Planning Bridge Retrofit Work to Correct Seismic-Related Deficiencies

High seismic- risk area[a]	Completed some retrofit work	Some retrofit work planned or in progress	Retrofit work not planned
Arizona	X		
California	X		
Idaho	X		
Illinois	X		
Nevada	X		
Tennessee	X		
Washington	X		
Utah	X		
Wyoming	X		
Alaska		X	
Arkansas		X	
Hawaii		X	
Kentucky		X	
Missouri		X	
Montana			X
Moderate seismic-risk area[b]			
Connecticut	X		
New York	X		
South Carolina	X		
Massachusetts		X	
New Jersey		X	
North Carolina		X	
Oregon		X	
Rhode Island		X	
Delaware			X
New Mexico			X
Virginia			X
Total	**12**	**10**	**4**

[a]State includes areas where acceleration coefficient is greater than .19g.

[b]State includes areas where acceleration coefficient is greater than .09g and equal to or less than .19g.

Bridge Seismic Safety Research

This appendix summarizes bridge seismic design and retrofit research sponsored by the Federal Highway Administration, other federal agencies, states, and private organizations.

Seismic Research Sponsored by FHWA

Since the 1970s FHWA has funded research on bridge seismic design and seismic retrofit methods and techniques. Following the 1971 San Fernando, California, earthquake, FHWA and the California Department of Transportation (CALTRANS) sponsored seismic research which led to the development in 1983 of a more comprehensive seismic design standard for new bridge construction, AASHTO's "Guide Specification for the Seismic Design of Highway Bridges" (Guide Specification). The Guide Specification contained much more detailed seismic design and construction details than those in AASHTO's Standard Specification for the Design of Highway Bridges. Research funded by FHWA also led to the development of two publications on seismic retrofit: "Seismic Retrofitting Guidelines for Highway Bridges," published in December 1983, and "Seismic Design and Retrofit Manual for Highway Bridges," published in May 1987. Since the mid-1970s FHWA has also published research on the seismic design of bridge foundations, earthquake-resistant bridge bearings, and seismic design for liquefaction potential at bridge sites.

Since the Loma Prieta Earthquake, FHWA's Structural Advisory Council has proposed spending $6 million in fiscal years 1992-97 on seismic research for both new construction and seismic retrofit of existing bridges. The objectives of the research, according to an FHWA official, are to update and clarify the AASHTO specifications for the design of new or replacement bridges while also conducting research to develop nationally applicable seismic retrofit measures and guidelines. According to an FHWA official, the research will require limited physical testing and will rely heavily on the research already being conducted by others in the aftermath of the 1989 Loma Prieta Earthquake. Of the $6 million, about $3.15 million will be spent on research applicable for seismic design for new-bridge construction, and about $2.85 million is planned for research in seismic retrofit. Early in fiscal year 1992, Congress authorized up to $12 million in funding between fiscal year 1992 and 1997 to study the earthquake vulnerability of highways, tunnels, and bridges on the federal-aid system and to develop and implement cost-effective retrofit methods to reduce such vulnerability.

Seismic Research Sponsored by Other Federal Agencies, States, and Private Organizations

At the federal level, several agencies besides FHWA have also undertaken bridge seismic research. For example, the National Institute of Standards and Technology is funding three studies during fiscal years 1990-91 to identify various methods for strengthening different types of bridges. A study funded by the U.S. Geological Survey is developing a model for state transportation departments to use in analyzing the effects of site conditions and soft soils on concrete box girder bridges, according to a Wayne State University researcher. Also, the National Cooperative Highway Research Program is funding a study to identify critical areas in need of revision in the 1983 AASHTO Seismic Design Guide Specification and is sponsoring research with CALTRANS on the response of pile-supported bridges subject to liquefaction.

The Federal Emergency Management Agency, in conjunction with the National Institute of Standards and Technology and several private sector organizations, is drafting a plan for the development of design and construction standards applicable to lifelines (including transportation infrastructure such as highways and bridges), according to a FEMA official.[1] The plan, which is to be completed by June 1992, will contain recommendations on ways federal regulatory authority can be used to expedite the implementation of such standards.

Many states have also conducted research on bridge seismic safety. Since the Loma Prieta Earthquake, CALTRANS has undertaken about $7 million worth of research on bridge seismic safety research projects. Research now under way or planned focuses primarily on techniques for strengthening bridge columns; retrofitting of multilevel and multicolumn bridges; the seismic response of bridge structures built on deep, soft soils; and retrofit techniques for long-span bridges such as those crossing the San Francisco Bay. Other states, such as Arizona, Illinois, Kentucky, Oregon, and Washington, have also completed or have in process seismic research in one or more of the following areas: research on methodologies to assess bridge vulnerability to earthquake damage, seismic retrofit designs applicable to their state, and the seismic resistance of bridge foundations.

Various earthquake engineering research centers have conducted or are conducting bridge-related seismic research, including the National Center for Earthquake Engineering Research at the State University of

[1]Lifelines refer to critical supply, disposal, transportation, and communications systems whose continued operation after an earthquake is vital for the health and safety of communities affected by earthquake damage. Examples of lifelines include electrical utilities or natural gas pipelines; sewers and water mains; highways and bridges; and telephones and telecommunications systems.

New York at Buffalo; the Applied Technology Council, Redwood City, California; the University of Nevada, Reno; the Earthquake Engineering Research Center at the University of California (UC), Berkeley; and UC campuses in Davis, Irvine, and San Diego.

Objectives, Scope, and Methodology

In an August 3, 1990, letter and in subsequent discussions, the Senate Committee on Environment and Public Works asked GAO to determine (1) states with areas where bridges may be damaged by moderate- to high-intensity earthquakes; (2) actions states have taken to identify and correct seismic-related bridge deficiencies; and (3) actions FHWA has taken, or needs to take, to assist states in addressing seismic deficiencies in bridges.

To address these objectives, we analyzed state seismic safety activities in most states (26 of 31) with moderate and high seismic-risk areas. (See app. I for a definition of moderate and high seismic areas.) These 26 states included all 15 states located in high seismic-risk areas and 11 of the 16 states located in moderate seismic-risk areas. The 11 states selected were Connecticut, Delaware, Massachusetts, New Jersey, New Mexico, New York, North Carolina, Oregon, Rhode Island, South Carolina, and Virginia. We selected these states to obtain diversity in size and geographic location.

In each state we conducted a telephone survey with the chief bridge engineer in the state transportation department to (1) obtain information about state seismic safety activities and (2) obtain views on activities by the Federal Highway Administration and the American Association of State Transportation and Highway Officials related to bridge seismic safety. We made site visits to the bridge engineering sections of state transportation departments in 6 of the 26 states: California, Kentucky, Missouri, New York, Oregon, and Washington.

During each site visit, we interviewed state bridge officials and obtained documents and reports pertaining to bridge seismic activities. We also interviewed federal officials responsible for bridge replacement and rehabilitation programs within the Federal Highway Administration in Washington, D.C., at FHWA regional offices, and at FHWA division offices in each of the 26 states contacted. We also contacted other officials responsible for earthquake hazard reduction programs at the Federal Emergency Management Agency in Washington, D.C.; U.S. Geological Survey in Washington, D.C., and Golden, Colorado; and the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. At each agency we obtained any documents, studies, or reports related to bridge seismic safety or earthquake hazards reduction.

In order to address objectives one and three, we interviewed officials with private organizations with an interest in bridge seismic safety: the American Association of State Highway and Transportation Officials;

the Transportation Research Board in Washington, D. C.; the National Center for Earthquake Engineering Research at the State University of New York, Buffalo; and the Earthquake Engineering Research Center at the University of California, Berkeley. We selected these groups based on their activities, interest, and knowledge related to bridge seismic safety. We also attended a symposium on Lifeline Earthquake Engineering sponsored by NIST in Gaithersburg, Maryland in September 1990 and a conference on "The Loma Prieta Earthquake—One Year Later" sponsored by the Bay Area Regional Earthquake Preparedness Project in October 1990 in San Francisco, California.

To assist us in evaluating technical issues associated with our review, we retained an earthquake engineering consultant, Dr. Ian Buckle, Deputy Director, National Center for Earthquake Engineering Research, State University of New York at Buffalo. The consultant's work focused on assessing the vulnerability of bridges to earthquake damage, identifying impediments faced by states in accelerating bridge seismic safety activities, and identifying additional actions FHWA could take to improve the seismic safety of existing bridges. Appendix II summarizes the consultant's work related to assessing the vulnerability of bridges to earthquake damage.

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