July 31, 2024

SEISMIC SAFETY OF CALIFORNIA BRIDGES

SELF-ASSESSMENT REPORT by the California Department of Transportation

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EXECUTIVE SUMMARY

Caltrans recognizes that improving the seismic resilience of the State's transportation network requires a long-term commitment. It has been more than 30 years since the last catastrophic earthquake occurred, causing considerable damage, and it is highly probable that another major earthquake will occur in the near future. It is therefore critical that Caltrans keeps seismic safety a priority, continues a vigorous, solution-focused seismic research program, and remains diligent in the development of improved seismic policy, standards, and design provisions.

Caltrans continually evaluates the seismic vulnerabilities of its highway bridges and regularly reports to the Seismic Advisory Board (Board), which was established by Caltrans after the 1989 Loma Prieta earthquake, on the progress made in reducing the risk of major damage or even collapse of its bridges after a major earthquake. The number of bridges with seismic vulnerabilities continues to change due to:

- Advances in seismology, geotechnical practices, and knowledge of seismic structural vulnerabilities
- Aging bridges with associated deterioration affecting seismic performance
- Retrofits or replacements of existing bridges with seismic vulnerabilities

It has been several years since Caltrans formally published a report documenting the progress made and the continuing efforts needed to improve the seismic resilience of bridges on the State transportation system. This report addresses the following three questions and provides recommendations on the continuing efforts needed to improve the seismic resilience of highway bridges.

What has Caltrans done to improve the seismic safety of the State's bridges?

Caltrans has invested over $12.2 billion in the retrofitting or replacing of 2,279 of the 13,214 bridges on the State Highway System using updated seismic design codes. Additionally, local agencies have invested more than $1.4 billion toward retrofitting or replacing approximately 1,190 of their 13,400 locally-owned bridges.

Caltrans has worked with the U.S. Geological Survey, California Geological Survey, Pacific Earthquake Engineering Research Center, and academia to quantify and update the potential seismic hazards California bridges are exposed to.

Caltrans has developed the Seismic Design Criteria, a compilation of state-of-the-art seismic design and analysis methodologies for designing new design bridges in California. Many of the methodologies in the Seismic Design Criteria have evolved from Caltrans' extensive research and seismic retrofit programs.

What is the expected performance of new and retrofitted bridges?

Expected performance depends on the type of bridge and the service that it provides. After a large earthquake, new bridges categorized as "important" or "recovery" are expected to perform well, but may be closed for a short time for inspection and to complete any minor repairs before being quickly returned to service. Bridges constructed or widened using post-1990 Seismic Design Criteria are expected to perform well with a minimal potential for collapse during a large earthquake.

The performance of retrofitted bridges is expected to be significantly better than those that have not been retrofitted. Bridges not retrofitted during the Seismic Safety Retrofit Program were evaluated and deemed, at that time, as likely to be able to withstand a design-level earthquake without collapsing.

It is expected that most bridges will not collapse, but past earthquakes have demonstrated that the variability in ground motions at any given location could lead to a bridge collapse. Bridges near the earthquake epicenter could have extensive damage and be out of service for several months and possibly require replacement.

What is Caltrans doing to further reduce the seismic risk to the State's bridges?

Since the 1989 Loma Prieta and 1994 Northridge earthquakes, continual improvements in seismic design strategies and methodologies for new and retrofitted bridges have drastically reduced the probability of a bridge collapse due to an earthquake. Improving seismic safety is an ongoing effort, and since many older bridges continue to remain vulnerable to seismic activity, Caltrans continues to:

- **Perform risk assessments of existing bridges.** Caltrans is continually assessing and identifying seismically-vulnerable bridges based on evolving knowledge, seismic research, and lessons learned from earthquakes that have occurred within and outside of California. Through research and testing, Caltrans continues to gain a better understanding of the seismic vulnerabilities of bridges.
- **Fund the seismic retrofit of bridges.** Although the Seismic Safety Retrofit Program has been completed, approximately 620 additional bridges on the State Highway System have been identified as being vulnerable to seismic activity through recent seismic screenings. Many of these bridges may need retrofitting or replacement. Caltrans continues to fund the seismic retrofit of these bridges through the State Highway Operation and Protection Program (SHOPP), with the goal of reducing this number by 70 percent by 2028.
- **Improve the seismic performance of new and retrofitted bridges.** Through the research and development of new and improved standards, the performance of new and retrofitted bridges will continue to improve. Caltrans has been at the forefront of seismic research and the development of design and construction standards and continues to fund research projects and further develop new seismic design standards.

INTRODUCTION

Following the 1989 Loma Prieta earthquake, Caltrans established the Seismic Advisory Board (Board), an independent body whose role is to advise Caltrans on seismic policy and best technical practices. In 2010, the Board released *Closing the Gap in the Race to Seismic Safety* [1]. In this report, the Board acknowledged Caltrans' progress in its efforts to achieve a safe transportation system. The Board also made the following recommendations:

- Complete the Toll Bridge Retrofit Program as expeditiously as possible
- Work with local agencies to complete the Local Agency Bridge Retrofit Program
- Work with the Board and the State government to keep seismic funding a priority
- Take an active role in the seismic assessment of all California transportation structures and systems
- Continue a vigorous, solution-focused seismic research program

This report documents the status and ongoing progress of Caltrans' efforts toward implementing the Board's recommendations from 2010. It also addresses the expected performance of the bridges that have been retrofitted or replaced and the continuing efforts needed to further reduce the seismic risk to the State transportation system.

MOVING PEOPLE AND GOODS

California's transportation system consists of a wide variety of physical assets. The most significant assets in terms of cost and extent are pavement and bridges. The California State Highway System consists of 50,259 lane miles of pavement and 13,189 bridges with an estimated bridge replacement cost of over $188 billion. [2].

Highway bridges are integral to the transportation system due to their function of carrying roadways over natural and manmade obstacles. Severe earthquake damage to California's bridges would greatly impact the State Highway System and would adversely impact the State's economy and the well-being of all Californians. When a bridge is out of service, it severs the system, disrupting traffic, preventing access to communities, and impacting post-earthquake emergency response. Extensive bridge repairs and construction can significantly delay the recovery of an affected region.

California's transportation system also includes assets owned by cities and counties, toll authorities, tribal governments, and state and federal agencies, including 13,400 locally owned bridges [2].

Other highway structures, such as highway embankments, retaining walls, and pavement, are also vulnerable to earthquake damage but, in comparison to bridges, are less likely to threaten life safety. Disruption from bridge damage or loss is apt to be more expensive and of longer duration than similar damage to other transportation assets.

WHY ARE CALIFORNIA BRIDGES AT RISK FOR EARTHQUAKES?

Bridges are often located in areas with poor soil conditions near rivers or bays or have an irregular geometry, leading to the bridge experiencing complex responses during an earthquake. Adding to the complexity, California is one of the most geologically diverse states in the country and has more earthquakes that cause damage to bridge and structures than any other state.

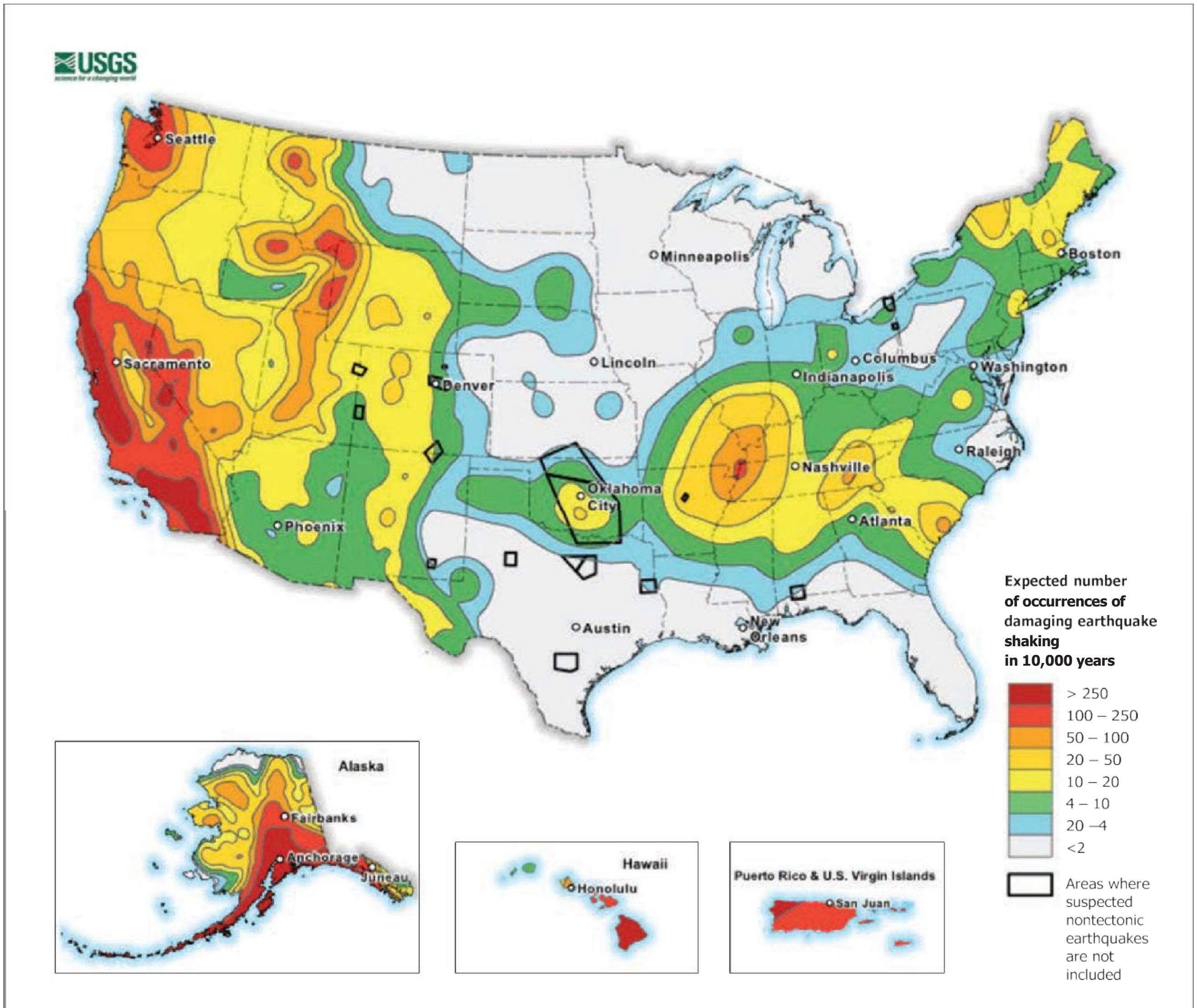

FIGURE 1: Frequency of Damaging Earthquakes in the U.S.

California has the following major seismic regions:

- **Cascadia Subduction Zone**. This zone is a tectonic plate boundary that stretches from Vancouver Island in Canada to Cape Mendocino in Northern California. It is a long, sloping subduction zone where the Juan de Fuca and Gorda plates move to the east and slide below the much larger continental North American plate. Megathrust earthquakes can occur at subduction zones with magnitudes exceeding 9.0.
- **San Francisco Bay Area.** This area straddles the boundary where two of the Earth's largest tectonic plates meet and are slowly moving past one another. When boundary faults break and the North American and Pacific plates move past each other, an earthquake occurs. At least eight faults in the Bay Area can produce earthquakes of magnitude 6.7 or larger.
- **Southern California Coastal Area**. This area is highly susceptible to earthquakes and their related effects. Numerous earthquake faults crisscross Southern California, and most people in this region live within 10 miles of an active fault. In this region, the San Andreas Fault system is capable of producing powerful earthquakes as big as magnitude 8.0.
- **Inland Empire.** This area is located along the San Andreas Fault from San Bernardino through the Coachella Valley to the Salton Sea. A large portion of the region's population lives within 50 miles of the San Andreas Fault and could be exposed to earthquakes as large as a magnitude 8. Many other faults such as the San Jacinto fault create smaller yet more frequent earthquakes.

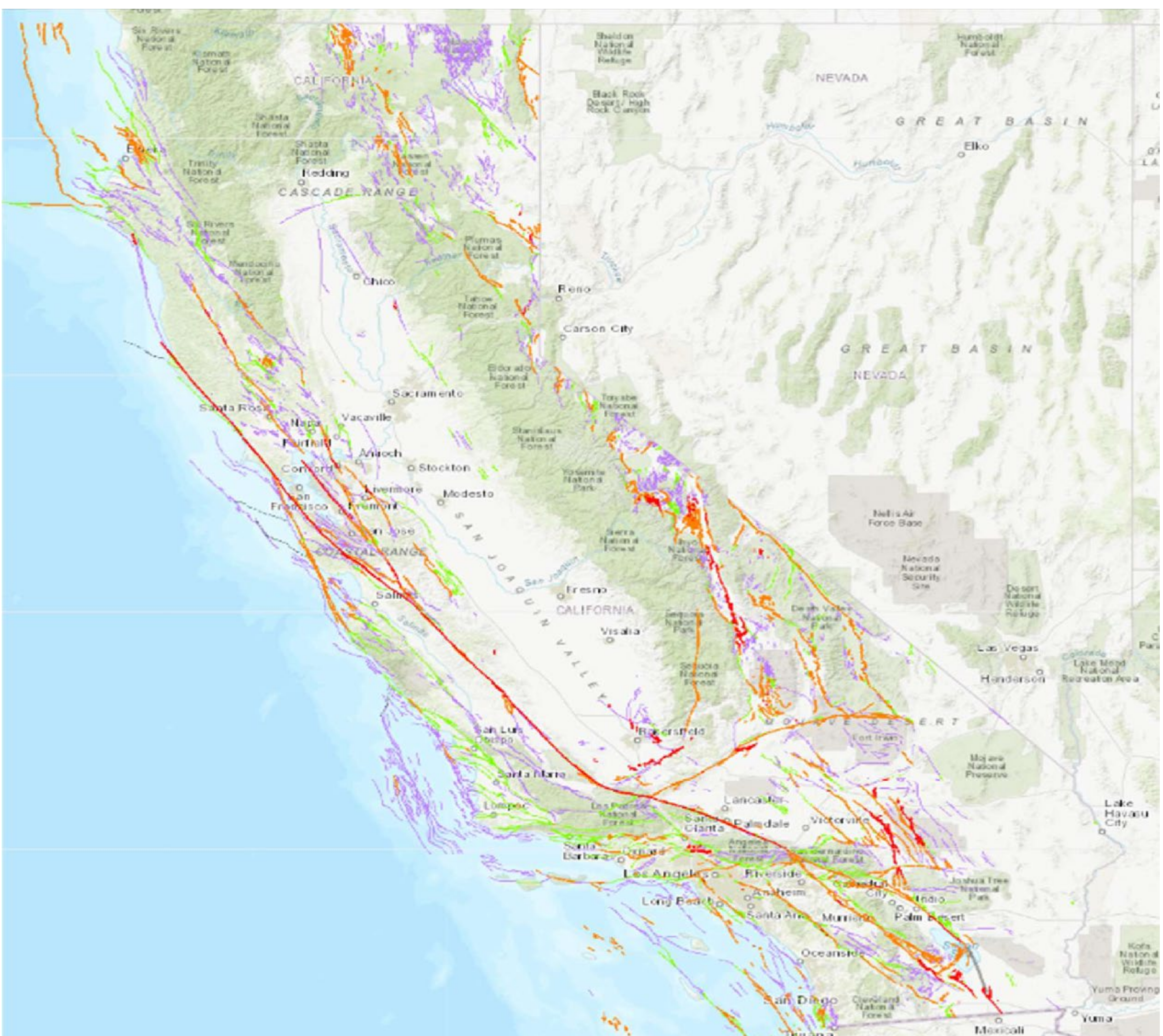

FIGURE 2: Major California Faults

IMPROVING DESIGN STANDARDS TO MEET SEISMIC RISK

Approximately 8,500 of the 13,214 bridges on the State Highway System were built between 1945 and 1975, before California had developed robust seismic design standards for its bridges. Figure 3 shows the number of bridges built between 1890 and 2023 that are still in service, and the number constructed using the modern seismic design criteria standards developed by Caltrans after the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes.

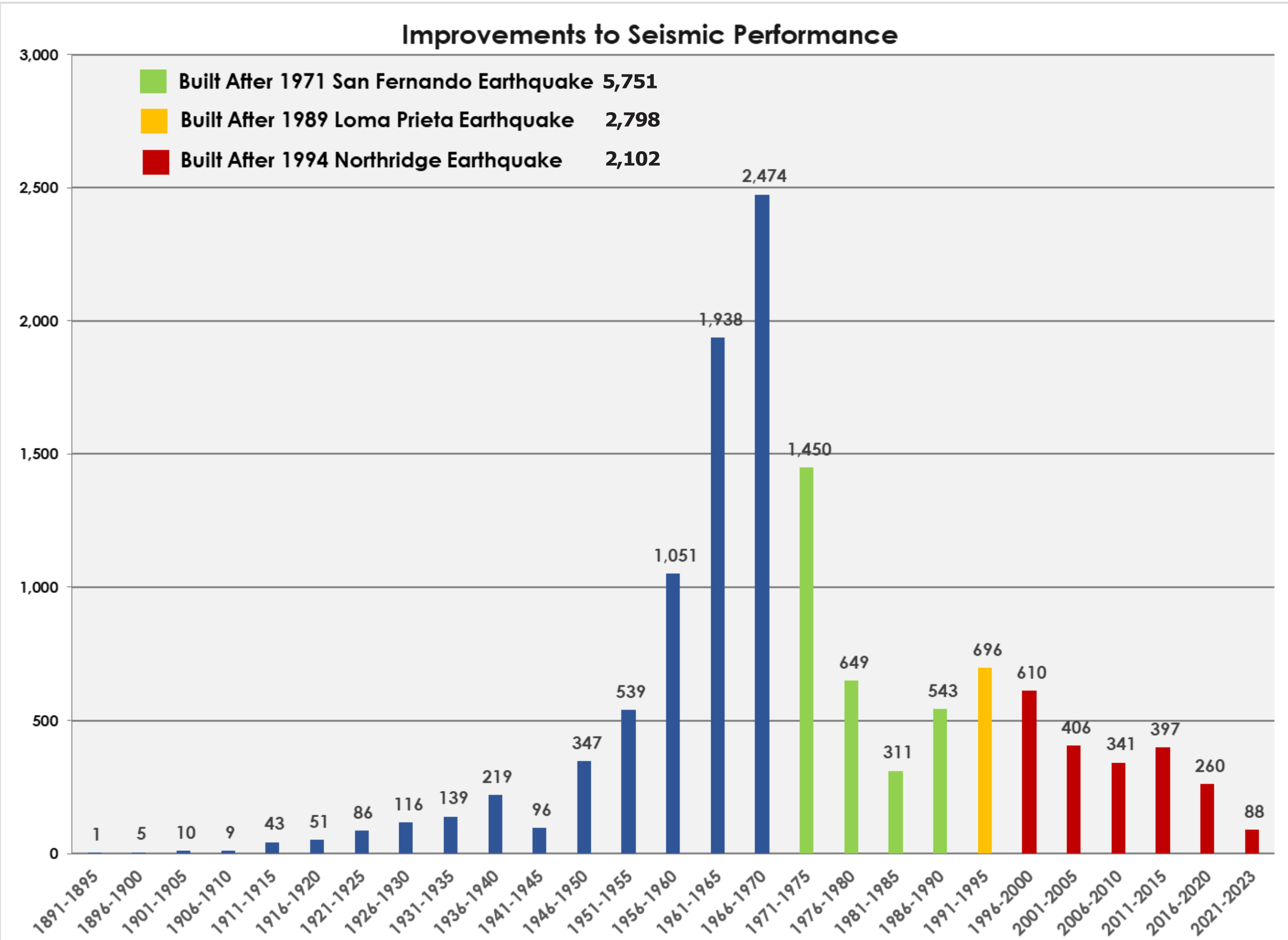

FIGURE 3: State Highway System Bridges In-Service By Year Built

The San Fernando, Whittier Narrows, Loma Prieta, and Northridge earthquakes caused collapse or severe damage to bridges in California. After each of these earthquakes, Caltrans addressed significant seismic-performance deficiencies and dramatically changed seismic design standards for bridges to reduce future vulnerabilities and damage. Below are summaries of key findings and actions taken from these major earthquakes:

1971 San ernando Earthquake (Magnitude 6.6)

The significance of highway earthquake safety was first identified in 1971, when the I-5/I-14 interchange and the Route I-210/I-5 separation and overhead in the San Fernando Valley collapsed. At the time of the earthquake, the I-5/I-14 interchange was under construction, which reduced the loss of life. Post-event investigation determined that there were four principal failure modes:

- Failure of the rebar lap splices at the base of columns
- Failure of the rocker bearings
- Collapse of the bridge spans due to excessive movement at the bridge joints, causing unseating of spans
- Shear and bending failure of the columns

These key findings led to a statewide Caltrans seismic retrofit program to install cable restrainers on existing highway bridges to limit the relative displacement across joints and prevent individual spans from falling. Other seismic issues relating to state and local bridges were also identified, and research to address these issues was initiated. However, budget limitations in the late 1970s limited seismic retrofitting solely to the installation of cable restrainers.

FIGURE 4: Lap Splices at the Column Base Caused Collapse at Route I-210/I-5 Separation and Overhead

1987 Whittier Narrows Earthquake (Magnitude 6.0)

In 1987, the Whittier Narrows earthquake nearly caused the collapse of the I-5/I-605 separation structure in Downey, CA. This magnitude 6.0 earthquake generated ground motions significantly smaller than what engineers commonly believed at the time to be a threat to bridges.

The key finding from this earthquake was that short columns were vulnerable to shear damage, as shown in Figure 5. This unexpected damage caused Caltrans to accelerate efforts to understand how bridges perform in earthquakes and how to improve future designs.

FIGURE 5: Shear Damage of Short Columns at I-5/I-605 Separation

1989 Loma Prieta Earthquake (Magnitude 6.9)

The Loma Prieta earthquake caused unprecedented damage to bridges throughout the San Francisco Bay Area, resulting in huge economic losses and disruption as far as 60 miles from the earthquake's epicenter. The collapse of a 1.6-mile section of the two-level, elevated Cypress Street Viaduct in Oakland took 41 lives. This collapse led to these key findings:

- Need for better structural framing requirements for bridges
- Inadequate transverse reinforcement detailing and reinforcement development in the multilevel viaduct joints contributed to the failures of the joints, as shown in Figures 6 and 7
- Recognition of the important and detrimental role of soft clay sites in amplifying earthquake shaking of bridges

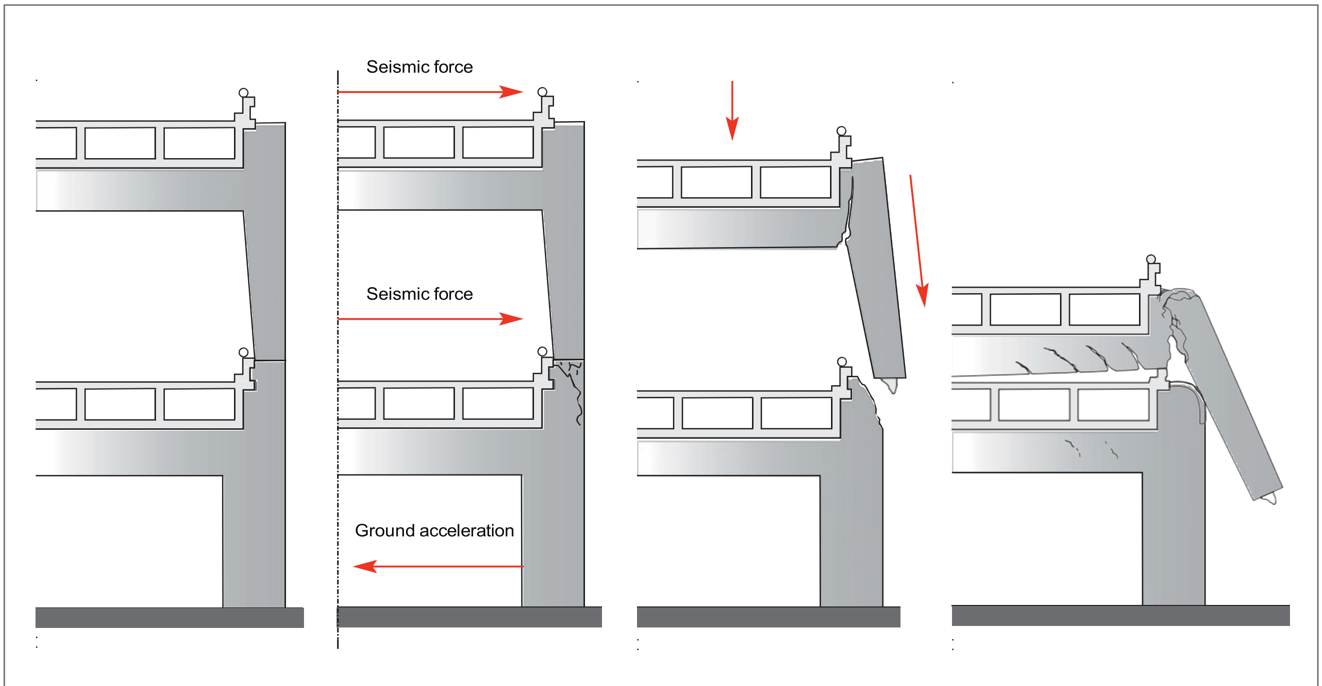

FIGURE 6: Collapse Sequence of the Cypress Street Viaduct

FIGURE 7: Collapsed Section of the Cypress Street Viaduct

Additionally, a section of the east span of the San Francisco–Oakland Bay Bridge unseated and collapsed onto the lower deck span, as shown in Figure 8. The unseating was due to structural framing issues at the junction of a flexible frame and a shorter stiffer frame, resulting in an insufficient hinge seat. The collapse led to one fatality and the closure of the bridge for 30 days to complete the repairs.

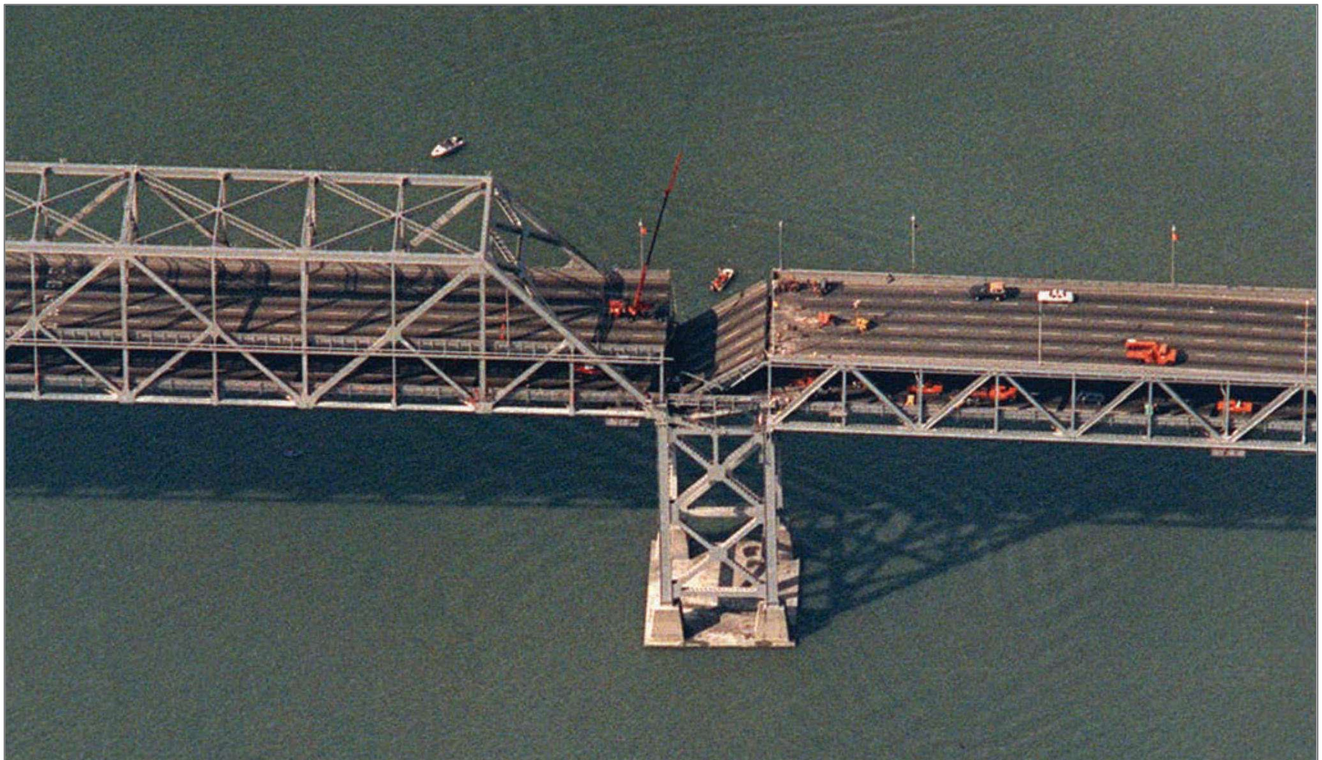

FIGURE 8: San Francisco–Oakland Bay Bridge Insufficient Hinge Seat

After the Loma Prieta earthquake, it was recognized that improving the seismic resistance of California's bridges would require a substantial and sustained investment in both research and retrofitting. Then-Governor Deukmejian appointed a Board of Inquiry to assess the State Highway System's deficiencies and provide recommendations for seismic safety. In 1990, the Board of Inquiry published C*ompeting Against Time* [3], which provided findings and recommendations for improving the seismic safety of California's transportation system. Governor Deukmejian issued Executive Order D-86-90 to implement the principal recommendations. The order stated:

> *"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"*

Subsequent executive orders set the performance objectives for the seismic retrofit programs, established the Caltrans Seismic Advisory Board, and laid the groundwork for a robust seismic research program for transportation structures. Bonds approved by both the legislature and public provided the resources needed for the seismic retrofit programs.

1994 Northridge Earthquake (Magnitude 6.7)

The 1994 Northridge earthquake caused the collapse of seven state highway bridges and damaged an additional 230 bridges with damage ranging from serious column cracks and abutment failures to bridge-approach pavement settlements. The damage to highway bridges was greater than expected; however, the 24 retrofitted bridges located in the area of strong ground shaking performed well. Many of the damaged bridges had already been identified as requiring retrofit, but this work had not been completed before the earthquake occurred. Figure 9 shows the lack of confinement reinforcement in a column built before 1971, which resulted in the failure of the Santa Monica Viaduct.

FIGURE 9: Failure of the Santa Monica Viaduct Column

Key findings from the Northridge earthquake include:

- Lack of balance in stiffness and mass from bridge support to bridge support
- Intense pulse-like ground motions near the ruptured fault exceeded the anticipated design motions and contributed to the collapse of several bridges
- High skews on bridges create seismic vulnerabilities
- Longer seat widths at supports are needed to accommodate seismic displacements

FIGURE 10: Failure of a Short Column at the I-14/I-5 Connector Separation and Overhead

After the Northridge earthquake, a design requirement for similar stiffnesses for columns in an individual bent and for bents in a longitudinal frame was implemented. Figure 10 shows the failure of a short column at Bent 2 at the I-14/I- 5 Connector Separation and Overhead. The structure's other columns were longer and more flexible. Figure 11 shows a schematic of a bridge with varying column heights in both a frame and an individual bent. The shorter stiffer columns are less flexible and will attract higher forces during an earthquake.

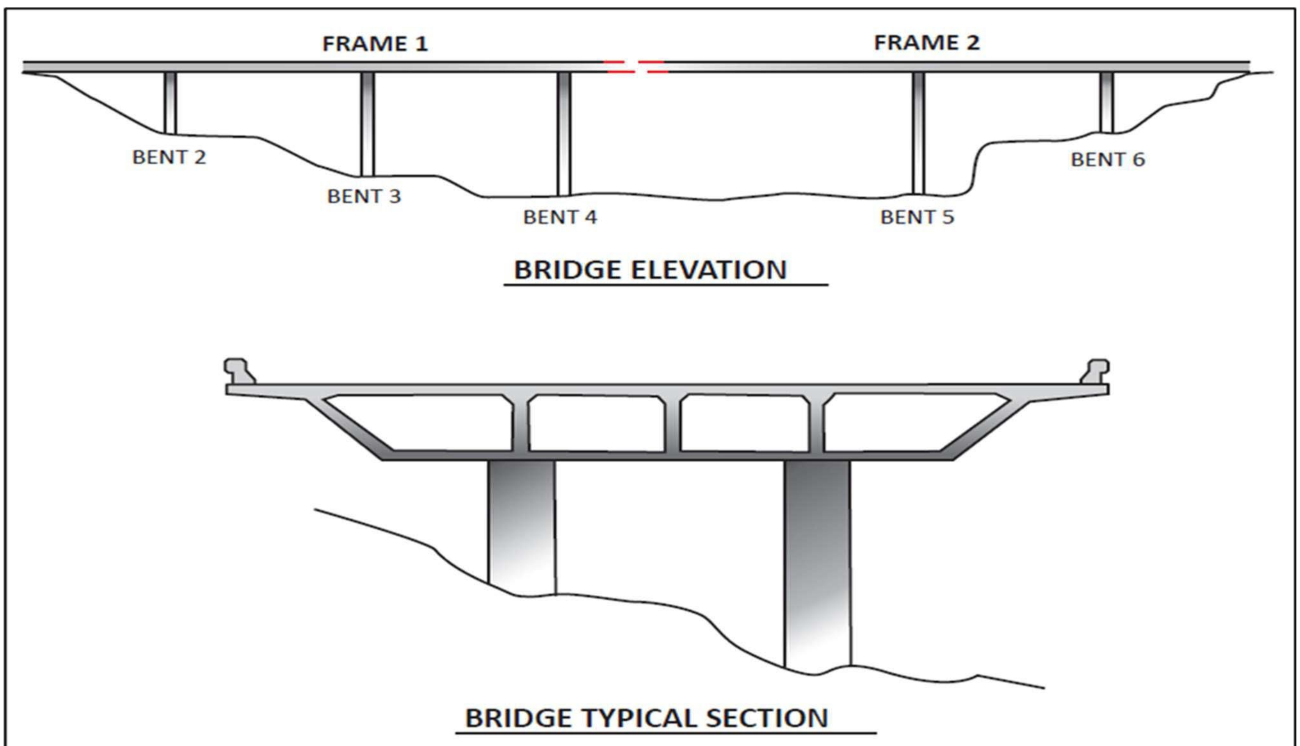

FIGURE 11: Bridge with Varying Column Heights

Figure 12 shows the unseating of bridge spans at Gavin Canyon Undercrossing on I-5, north of the I-14/I-5 interchange. The collapse can be attributed to complexities arising from the 66-degree skew of the abutments and expansion joints, as well as the 8-inch expansion joint seat widths. The bridge had been retrofit with expansion joint restrainers; however, these were not sufficient to keep the spans from unseating.

After the Northridge earthquake, Caltrans renewed its efforts to mitigate the seismic hazards posed to California bridges with a significant seismic retrofit program.

FIGURE 12: Unseated Highly-Skewed Bridge Spans at the Gavin Canyon Bridge

IMPROVING THE SEISMIC SAFETY OF BRIDGES

Since the 1971 San Fernando earthquake, Caltrans has continued to develop and improve seismic design standards for new construction based on the lessons learned from each subsequent major earthquake. These improvements include:

- Increasing the transverse reinforcement and improving the continuity of main reinforcement in bridge columns
- Eliminating vulnerable lap splices in reinforcement that connect footings to the columns
- Increasing the minimum seat widths at expansion joints, abutment seats, and hinges
- Developing site-specific ground-shaking hazards for designing bridges and a capacity-based design method that relies on structural column fuses to limit seismic forces
- Requiring similar stiffness for columns in an individual bent and for bents in a longitudinal frame
- Establishing improved seismic requirements for the development lengths and splices in reinforcement

After the 1989 Loma Prieta earthquake, new legislation mandated and funded programs to seismically retrofit—or replace—State Highway System, toll, and local bridges. Although the Bridge Seismic Retrofit Programs have concluded for bridges on the State Highway System, Caltrans continues to fund Bridge Seismic Restoration Projects through its State Highway Operation and Protection Program (SHOPP).

Table 1: Funding for Bridge Retrofit and Replacement Projects

	Number of Bridges	Bridges Retrofitted or Replaced	Cost (Billions)*
State Highway System	13,214	2,278	$3.2
Toll Bridges	9	9	$9.4
Local Bridges	13,400	1,192	$1.4

Retrofitting State Highway System Bridges

In 1990, Caltrans screened all State Highway System bridges for seismic vulnerabilities that could potentially lead to a bridge collapse during a large earthquake. These seismic vulnerabilities included poor structural details and proximity to known earthquake faults, where strong ground shaking could occur. The bridges were evaluated using a risk-based algorithm. At the time of the initial screening, most bridges were deemed adequate to survive the then design-level earthquake without retrofitting. A design-level earthquake is a theoretical earthquake event used to check the seismic resilience of a structure. Over 25 percent of the approximately 12,000 State Highway System bridges in service at the time of the original screening were retrofitted or replaced to lower or significantly minimize the probability of a collapse during a large earthquake. Figure 13 shows typical bridge retrofit strategies including column casings, enlarged foundations, and pipe seat extenders.

Since 1990, Caltrans has diligently implemented the directions set forth in Governor Deukmejian's Executive Order D-86-90 through the Seismic Safety Retrofit Program. In March 1996, voters approved Proposition 192 (Seismic Retrofit Bond Act of 1996), which provided $2 billion to finance the retrofit of State highway bridges, overpasses, and interchanges These programs have improved the performance and life safety of the State's bridges through improvements to the seismic design standards for new bridges and retrofitting existing bridges.

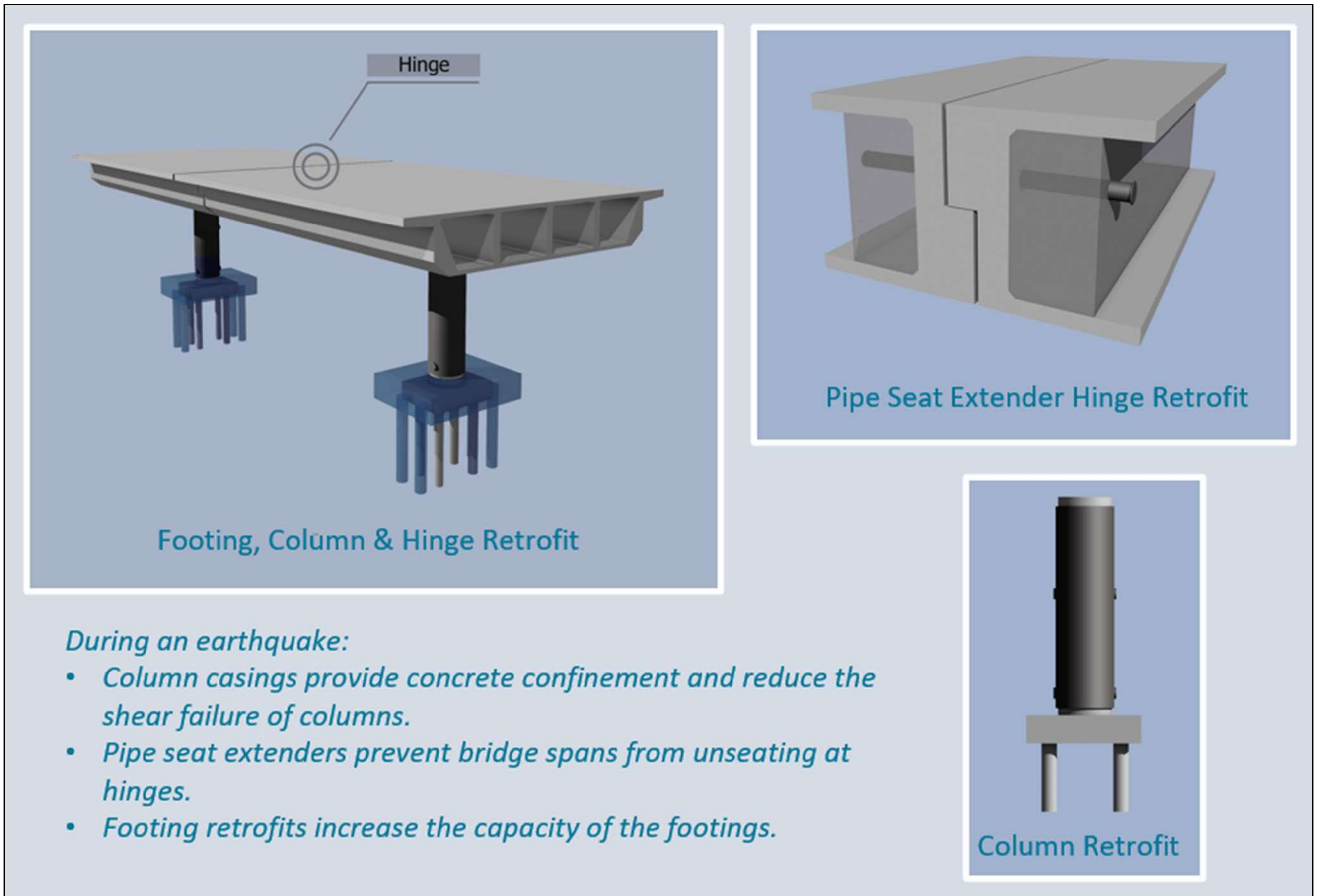

FIGURE 13: Seismic Retrofit Strategies for Bridges

Improving the Seismic Performance of Toll Bridges

In 1994, Caltrans initiated the Toll Bridge Seismic Safety Program to improve the seismic performance of seven of the State's nine toll bridges. In March 1996, voters approved Proposition 192 (Seismic Retrofit Bond Act of 1996), providing $2 billion to finance the retrofit of State highway bridges, overpasses, and interchanges, of which $650 million was dedicated to the seven San Francisco Bay Area toll bridges. Senate Bill 60 (August 1997), Assembly Bill 1171 (September 2001), and Assembly Bill 144 (July 2005) provided additional funding to complete the Toll Bridge Program retrofit projects. In 2009, Assembly Bill 1175 added the Dumbarton and Antioch toll bridges to the program. The Antioch Bridge retrofit was completed in 2012, and the Dumbarton Bridge retrofit was completed in 2013. The seismic retrofit of the Vincent Thomas Bridge, San Diego–Coronado Bay Bridge, Carquinez Bridge, Benicia-Martinez Bridge, San Mateo–Hayward Bridge, Richmond–San Rafael Bridge, West Spans of the San Francisco-Oakland Bay Bridge, and the replacement of the East Spans of the San Francisco–Oakland Bay Bridge have all been completed.

FIGURE 14: Bay Area Seismic Retrofit Program for Toll Bridges

The design basis for the Toll Bridge Seismic Safety Program was well developed and benefited from research findings. The engineering models and analysis procedures were state-of-the-art and laid the groundwork for what is now the state of the practice for earthquake engineering of long-span bridges. The nine toll bridges are expected to meet the projected performance of life safety and serviceability after an earthquake. In the case of the new section of the Bay Bridge and the new Benicia-Martinez Bridge, an even higher performance standard was implemented with an expectation of no or minimal damage and a return to full service immediately following a major earthquake [4].

Retrofitting California's Locally Owned Bridges

A Local Bridge Seismic Safety Retrofit Program was initially mandated by Senate Bill 36X in 1989. This emergency legislation provided funding assistance for public bridges owned by local agencies to achieve compliance with current seismic safety standards. All 12,500 locally owned bridges in service at that time were evaluated for earthquake vulnerabilities, of which 1243 bridges were identified as having potential earthquake vulnerabilities. In November 2006, voters passed Proposition 1B (Highway Safety, Traffic Reduction, Air Quality and Port Security Bond Act of 2006), which established a $125 million Local Bridge Seismic Retrofit Account to provide matching funds to complete bridges in the Local Bridge Seismic Retrofit Program. As of December 31, 2023, 1,205 local bridges have been retrofitted, replaced, or removed from the program, with an additional 25 bridges in construction and 13 bridges in design that remain in this program. Caltrans provides oversight and assistance to this program through its Local Assistance Highway Bridge Program.

Retrofitting State Highway System Bridges

Caltrans Seismic Design Criteria (SDC) [5] is a compilation of state-of-the-art seismic design and analysis methodologies for designing new bridges in California. Many of the methodologies in the Seismic Design Criteria have evolved from Caltrans' extensive research and seismic retrofit programs.

The 1999 Seismic Design Criteria adopted a performance-based approach by specifying minimum levels of structural system and component performance, analysis, and design practices for ordinary standard bridges. Ordinary standard bridges (further defined on page 19) are designed for life safety and might experience major damage during an event, but have a minimal probability of collapse. Bridges with nonstandard features or operational requirements above and beyond the ordinary standard bridge will require project specific seismic design requirements in addition to those specified by the Seismic Design Criteria.

The Caltrans 1999 Seismic Design Criteria changed the fundamental design philosophy for new bridges, shifting from a force-based assessment of seismic demand and capacity to a displacement-based assessment of seismic demand and capacity—designing for flexibility rather than strength. More flexible bridge components attract less earthquake energy, but because of their ductile nature, they must be designed to handle greater deflections during an earthquake.

Caltrans Seismic Design Criteria includes the following design principles:

- Earthquakes and the resulting ground shaking are assessed using probabilistic scientific tools
- Bridges are designed to dissipate the seismic energy while accommodating the deformation demands
- Critical components of bridges, such as the superstructure, column cores, and foundations, are designed to be capacity protected to carry their self-weight, thus minimizing the probability of collapse
- Seismic energy is directed to predesignated locations (called plastic hinges) in columns and shafts and to soils behind abutments
- Plastic hinges must be resilient (ductile) and tolerate large rotations without degradation, while limiting the force transfer to other bridge components

EXPECTED SEISMIC PERFORMANCE OF NEW AND RETROFIITTED BRIDGES

The seismic resilience of California's bridge system is measured by the ability to decrease the probability of failure and minimize the length of time that a bridge is out of service after an earthquake. The goal is to diminish the consequences of a failure, such as loss of life and economic and social hardships, and to be able to recover quickly and reestablish normal services.

Most of the older bridges evaluated in the early 1990s were deemed capable of withstanding a major earthquake without retrofitting, although those near the epicenter could be damaged enough to be out of service for several months, and some would likely require replacement. Collapse is not expected for most of these bridges. However, past earthquakes have demonstrated that the extreme variability in ground motions at any given location could lead to a bridge collapse. [4]

Expected Seismic Performance of New Bridges

New bridges designed to meet the seismic design standards developed after the Loma Prieta earthquake are expected to have a low probability of collapse. However, bridges categorized as "important" or "recovery" are designed to higher seismic standards and are expected to perform well with little damage or no damage, although they may be closed for a short period of time for inspection and while minor repairs are being performed.

Investigations of bridges after the 2023 magnitude 7.8 Turkey earthquake found that the bridges performed well with some damage but there was no knowledge of any bridge collapses. These bridges were designed using similar seismic design standards to that of California, which bodes well for the expected seismic performance of new bridges in California. [6]

Expected Seismic Performance of Retrofitted Bridges

The seismic performance of bridges assessed and retrofitted is expected to be significantly better than those that have not been retrofitted. However, prior to the Northridge earthquake, only the most vulnerable components of bridges were retrofitted. These partially retrofitted bridges were reevaluated as part of Caltrans' 2015 seismic screening of the bridges on the State Highway System, and those bridges deemed vulnerable have been earmarked for additional evaluation and potentially further retrofit.

Existing bridges are retrofitted to only reduce the probability of collapse and loss of life, since it is not typically economically feasible to retrofit a bridge that has been in service for several decades to the performance level of a new bridge. Designers must balance retrofit costs to achieve the goal of no collapse with the cost of constructing a new bridge. In some circumstances, the cost to retrofit a bridge was nearly that of replacement, so many older bridges have been replaced in lieu of retrofitting.

California has not had a major earthquake in a heavily populated area of the state since the 1994 Northridge earthquake. A survey completed after the Northridge earthquake found that all 63 seismically retrofitted bridges within the area of strong shaking performed well.

Additionally, in the 2014 magnitude 6.0 South Napa earthquake, all 54 of the retrofitted bridges within the area of strong shaking performed well. Before the earthquake, all 412 State Highway System bridges in Solano, Napa, and Sonoma counties had been screened for seismic vulnerabilities. The Route 37 Napa River Bridge, which was extensively retrofitted in 1996, experienced minimal damage and was reopened to traffic shortly after inspection. The Sonoma Creek Bridge, which was retrofitted in 1999, also had no damage. The performance retrofitted bridges in recent earthquakes demonstrates an increase in the seismic resilience of these bridges.

CALTRANS EFFORTS TO REDUCE SEISMIC RISK

Caltrans Office of Earthquake Engineering, Analysis, and Research supports the effort to reduce the seismic risk to the bridges on the State Highway System through their continual seismic assessments of existing bridges. These seismic assessments are updated regularly to include knowledge gained from the seismic research program, lessons learned from past earthquakes, and the development of improved seismic policy, standards, and design provisions. The Office of Earthquake Engineering, Analysis, and Research also manages the Caltrans Seismic Research Program and provides seismic-design-related support to Caltrans' and consultant bridge designers.

Assessing and Prioritizing Seismically Vulnerable Bridges

Seismically vulnerable bridges have the potential for damage and even the possibility of collapse. Caltrans regularly assesses the seismic hazard and performance of the State Highway System bridges to ensure that bridges built or retrofitted with earlier seismic design standards can be expected to perform sufficiently to prevent collapse. The Caltrans seismic-screening database contains the latest resiliency data for each bridge in the state bridge inventory.

In the 2015 seismic screening [7], Caltrans applied a newly developed algorithm to better identify weaknesses and prioritize seismically vulnerable bridges, which considered:

- Bridges crossing active faults
- Bridges located in soils with high liquefaction potential
- Bridges with increased ground-shaking hazards
- Improvements in seismology and seismic analysis
- Bridge vulnerabilities not addressed in previous retrofit programs

In the 2015 screening, 553 bridges were identified as seismically vulnerable. In the 2019 seismic screening [8], Caltrans identified additional bridges with potentially vulnerable lap splices in the main reinforcement at the base of columns and prioritized their retrofit, bringing the number up to 642 bridges. Based on the most recent seismic screening, a new seismic priority list was developed in 2020. In an effort to focus on the highest priority seismic work first, a financially constrained prioritized list consisting of 243 bridges was developed resulting in a reduction of the total seismic need identified in the State Highway System Management Plan (SHSMP). This number is constantly changing as retrofits or bridge replacements are completed, or identified bridges are further analyzed and deemed to not need a retrofit. As seismic work is completed, this financially constrained list will be amended to incorporate lower priority identified seismic needs.

Caltrans' performance target in the 2023 State Highway System Management Plan is to reduce the number of most seismically vulnerable bridges by 70 percent by 2033. The 2024 State Highway Operation and Protection Program (SHOPP) funds the repair and preservation, emergency repairs, safety improvements, and limited highway operational improvements on the State Highway System. For the 2024 SHOPP, Caltrans will fund $2.2 billion in bridge projects over four years. These projects include bridge rail upgrades, bridge and tunnel rehabilitation, bridge scour mitigation, bridge seismic restoration, and bridge goods movement upgrades. On average, Caltrans will spend $62 million over the next five years on bridge seismic restoration projects.

Since the development of the prioritized list in 2020, construction has been completed on 58 (17%) of the bridges on the prioritized list, 19 (10%) of bridges are currently in construction, and 82 (34%) bridges have been programmed for construction or are in the project development phase. Additionally, 8 bridges (3%) were further analyzed and did not require a seismic retrofit or were determined to be a locally owned bridge. The remaining bridges are being advanced to the project development phase and will be incorporated into future SHOPP and SHSMP updates. Caltrans is currently on track to meet the performance target to reduce the number of most seismically vulnerable bridges by 70 percent as outlined in the 2023 SHSMP.

Current policies also require that bridge engineers assess the seismic performance of every bridge that is widened or undergoes major rehabilitation. If needed, bridge retrofit work is either incorporated into the project or earmarked for a follow-up bridge retrofit project.

World Leading Seismic Research

Since the 1971 San Fernando earthquake, Caltrans has been recognized as both a national and international leader in seismic research and the development of seismic policy, standards, and design provisions for bridges. Caltrans takes this vital role seriously as part of its core mission of managing California's transportation-related assets, and continues to advocate for and advance further innovations to better protect the well-being of its people and the prosperity of the State. Achieving these objectives requires continual investment in research and development of analytical procedures and tools, and learning from major seismic events.

State-of-the-art analytical procedures and tools are essential to accurately assess a bridge's seismic performance to ensure that engineers are designing bridges that minimize the probability of loss of life and reduce the cost associated with a severely impaired or inoperable transportation system after a major earthquake. These tools include simulation modeling to better predict the seismic response of the bridge; advanced probability-based risk-assessment methods that consider uncertainties in seismic hazards and structural performance; and more efficient field evaluation methods for bridge condition assessment, maintenance, and rapid post-earthquake damage assessment and repair.

Caltrans continues to work with the U.S. Geological Survey, California Geological Survey, Pacific Earthquake Engineering Research Center, and academia to quantify and update the potential seismic hazards bridges are exposed to, including ground shaking, fault crossing, liquefaction and lateral spreading, and tsunamis, to develop a database of representative site-specific design spectra, ground-motion histories, and possible surface offsets due to fault rupture. This information will be used for future seismic vulnerability assessments and design. Additionally, through a partnership with the U.S. Geological Survey, Caltrans implemented the ShakeCast tool, a post-earthquake bridge inspection prioritization system that highlights bridges and buildings most likely to be damaged after an earthquake.

Probabilistic Methodology and Performance Criteria

Caltrans no longer designs or retrofits bridges to a specific earthquake magnitude. Instead, Caltrans uses a probabilistic methodology that evaluates a multitude of earthquake scenarios for a given bridge location. For example, the methodology considers the bridge's distance from earthquake faults, the expected ground motion intensity at the bridge site, and the soil characteristics beneath the bridge.

The seismic hazard used to design ordinary highway bridges corresponds to an annual return period of 975 years. Another way of describing the seismic hazard is an earthquake large enough to induce ground shaking at the bridge has a 5 percent probability of occurring or being exceeded over any 50-year period.

Caltrans, in collaboration with the Seismic Advisory Board, created the following seismic performance criteria categories for bridges:

Important Bridges

Important bridges are essential for regional emergency response. An important bridge is designed to meet the highest standards and is expected to remain in service with no or minimal damage, even after a large earthquake. The San Francisco–Oakland Bay Bridge East Span replacement and the new Benicia-Martinez Bridge have been both designated as important bridges since they are complex bridges located on lifeline routes. The State's other toll bridges were retrofitted to withstand earthquakes of similar magnitude and intensity as an important bridge, but they are not expected to be immediately put back into service after a large earthquake.

Recovery Bridges

Recovery bridges serve as vital links for rebuilding damaged areas and providing access to the public shortly after an earthquake. They are designed for enhanced performance above "ordinary" bridges but less than the performance of "important" bridges. This category was added to the 2019 Seismic Design Criteria, version 2.0 [5]. Recovery bridges are expected to have minimal to moderate damage with service limited to emergency vehicles for bridges with moderate damage.

Ordinary Bridges

Ordinary bridges are categorized as either standard or nonstandard. Bridge engineers design standard bridges, such as typical highway undercrossings and overcrossings, to minimize the probability of collapse by following standardized seismic design and analysis methodologies. The Seismic Design Criteria that Caltrans developed in the 1990s primarily addressed ordinary standard bridges. Even though an ordinary bridge designed to the current SDC might suffer significant damage, it is expected to be able to return to service within a reasonable amount of time.

Nonstandard or complex bridges, like cable-supported, arch, or other unusual structure types, are often designed for enhanced seismic performance, reflecting their complex response, cost, and the monetary cost to repair or replace them after a major earthquake. Additionally, the SDC requires that a Safety Peer Review team be established for these nonstandard or complex bridges.

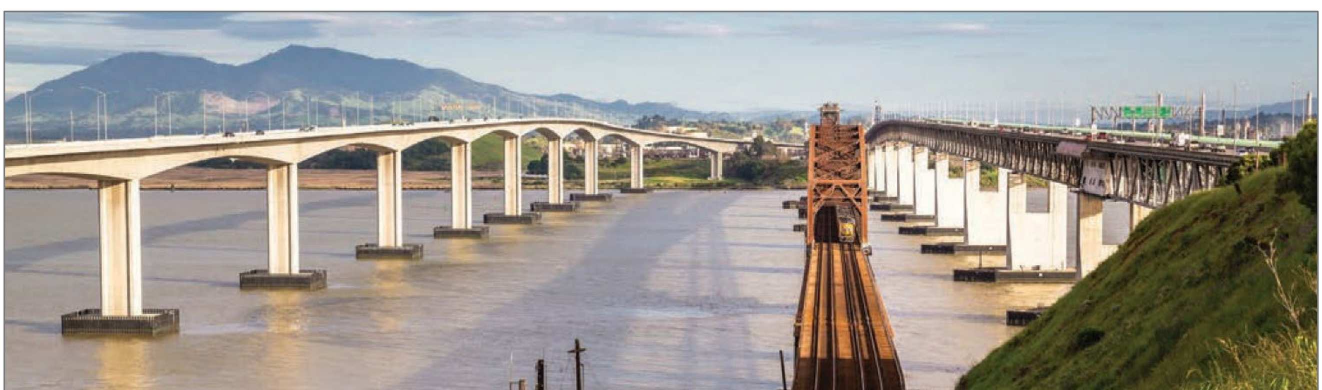

FIGURE 15: New Benicia-Martinez Bridge Is Designed to Meet Highest Standards

Accelerated Bridge Construction

In partnership with the Federal Highway Administration, Caltrans is developing bridge structures that are faster and more economical to construct that are also resilient to earthquakes. Accelerated bridge construction techniques allow for faster recovery from a major earthquake with the use of precast concrete components to construct bridges quickly while still meeting Caltrans seismic design standards and performance requirements.

FIGURE 16: Echo Summit Bridge Replacement Project

The Echo Summit Bridge Replacement was completed in October 2022. The project replaced a bridge that had served motorist travelling to and from Lake Tahoe since 1939. This project incorporated precast, prestressed girders, concrete overlays, precast columns, and precast abutments. Seven 96-foot girders were connected with ultra-high performance concrete to enhance the durability of the structure. The new bridge replaced a 24-foot road width with a 30.75-foot road width to provide for safer 12-foot lanes and increased shoulder widths.

FIGURE 17: Echo Summit Precast Girders

FIGURE 18: Completed Echo Summit Bridge

MOVING FORWARD

Since the 1971 San Fernando, 1989 Loma Prieta, and 1994 Northridge earthquakes, continual improvement in the seismic design of new bridges and the retrofitting of existing bridges has drastically reduced the probability of a bridge collapse due to an earthquake. However, recent seismic screenings have shown that many older State Highway System bridges—most of them located in the Bay Area and Southern California—are seismically vulnerable.

Caltrans has had to balance the efforts of improving seismic safety against other significant transportation needs that demand resources and funding. The passing of the Road Repair and Accountability Act (SB 1) and the implementation of the California Transportation Asset Management Plan has provided increased transportation funding and a greater focus on asset management. In addition to the funding provided by SB1, the Inflation Reduction Act (IRA) and the Infrastructure Investment and Jobs Act (IIJA) will allow California to invest $180 billion in new infrastructure over the next decade. However, it is important for Caltrans to use these transportation dollars wisely and develop innovative solutions to improve seismic safety through research and the continuing development of seismic policy, standards, and design provisions.

Additionally, Caltrans is reviewing the resiliency of the State's transportation system in order to make evidence-based decisions on where to focus seismic safety improvements. Preventing loss of life is the primary goal, but rapid emergency response and timely economic recovery after an earthquake are also crucial. Caltrans is focusing on the design and construction of the next generation of bridges to increase resiliency in order to meet the expectations of Californians following a seismic event.
There is no finish line for seismic resiliency of bridges on the State transportation system, and Caltrans recognizes the importance of making incremental improvements with a focus on investing in research that helps to evolve the state of practice in earthquake engineering and to incorporate lessons learned from seismic events around the world. Caltrans must also remain diligent about routinely evaluating the seismic vulnerability of its bridge inventory using updated risk assessment algorithms. These long-term investments ensure that Caltrans continues to advance seismic resiliency even when other extreme events vie for attention and resources.

Lastly, local bridges play an important role in the resiliency of the State transportation system. Caltrans must continue to work with local agencies to promote the importance of their seismic retrofit programs to ensure emergency response and mobility after a major earthquake.

CONCLUSION

This report provides an assessment of what has been done to improve the seismic resilience of bridges in California, describes how bridges are likely to perform during the next major earthquake, and what is being done to further reduce the probability or risk of major damage to or collapse of bridges during a large earthquake. To that end, this report answers the following three questions.

What has Caltrans done to improve the seismic safety of the State's bridges?

- Caltrans has invested $12.2 billion in retrofitting or replacing 2,279 of the 13,214 bridges on the State Highway System, using updated seismic design standards. Additionally, local agencies have invested more than $1.4 billion toward retrofitting or replacing 1,204 of the 13,400 locally-owned bridges.
- Caltrans has worked with the U.S. Geological Survey, California Geological Survey, and academia to quantify and update the potential seismic hazards bridges are exposed to.
- Caltrans has developed the Seismic Design Criteria, a compilation of state-of-the-art seismic design and analysis methodologies for designing new bridges in California. Many of the methodologies in the Seismic Design Criteria have evolved from Caltrans' extensive research and seismic retrofit programs.

What is the expected performance of new or retrofitted bridges?

- After a large earthquake, new bridges categorized as "important" or "recovery" are expected to perform well, but may be closed for a short time for inspection and to complete any minor repairs before being quickly returned to service.
- Bridges constructed or widened using post-1990 Seismic Design Criteria are expected to perform well with a minimal potential for collapse during a design-level earthquake.
- The performance of retrofitted bridges is expected to be significantly better than those that have not been retrofitted.
- It is expected that most bridges will not collapse, but past earthquakes have demonstrated that the variability in ground motion at any given location could lead to a bridge collapse. Additionally, bridges near the earthquake epicenter could have extensive damage and be out of service for several months and possibly require replacement.

What is Caltrans doing to further reduce the seismic risk to the State transportation system?

- Caltrans is continually assessing and identifying seismically vulnerable bridges based on evolving knowledge, seismic research, and lessons learned from earthquakes that have occurred within and outside of California. Through research and testing, Caltrans continues to gain a better understanding of the seismic vulnerabilities of bridges.

- Although the Seismic Safety Retrofit Program has been completed, approximately 620 additional bridges on the State Highway System have been identified as being vulnerable to seismic activity through recent seismic screenings. Many of these bridges may need retrofitting or replacement. Caltrans continues to fund the seismic retrofit of these bridges through the State Highway Operation and Protection Program (SHOPP), with the goal of reducing this number by 70 percent by 2033.
- Through the research and development of new and improved standards, the performance of new and retrofitted bridges will continue to improve. Caltrans has been at the forefront of seismic research and the development of design and construction standards and continues to fund research projects and further develop new seismic design standards.
- Caltrans recognizes that improving the seismic resiliency of the bridges on the State's transportation system requires a long-term commitment to meet the goal of safety and sustainability. It has been more than 30 years since the last catastrophic earthquake caused considerable damage to the State's transportation infrastructure, and it is highly probable that a major earthquake will occur in the future. In view of the extreme seismic risk and the high value of California's economy, Caltrans continues to make funding for seismic retrofit projects a priority, takes an active role in the seismic assessment of all bridges and transportation structures, and supports a vigorous solution-focused seismic research program.

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