Caltrans Highway Structures

By Mark Yashinsky

Every damaging California earthquake has resulted in changes to the California Department of Transportation's (Caltrans') seismic practice. The most significant changes occurred after the **1971 San Fernando Earthquake**. Bridges at that time were designed for a small seismic force, which resulted in extensive damage to bridges and interchanges during the earthquake.

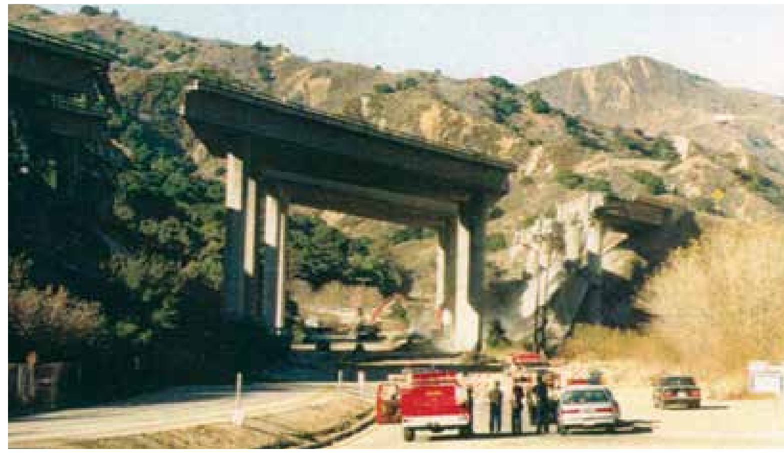

Figure 1. Gavin Canyon Bridges.

Immediately afterward, Caltrans wrote construction change orders requiring more transverse reinforcement and continuous main reinforcement in bridge columns and eliminating a vulnerable lap splice connecting the footing to the column. Also, the minimum seat length at expansion joints, abutment seats, and hinges went from 12 inches to 18 inches (and later to 24 inches). Other changes included the development of a site-specific ground shaking hazard for designing bridges and a capacity-based design method that relied on structural column fuses to limit seismic forces. Caltrans also started a seismic retrofit program to address the many existing bridges that had been under-designed for earthquakes. The San Fernando Earthquake was also the start of the practice of Caltrans sending out a reconnaissance team of licensed engineers to study the damage and write a report with lessons learned, a practice that has continued for every subsequent large earthquake.

The **1987 Whittier Narrows Earthquake** was another turning point in Caltrans seismic design of bridges. The previous retrofit program relied on cable restrainers to limit displacement and prevent column damage, but shear damage to the short columns on the Route 605/5 Separation (53 1660) generated enough concern to begin a new retrofit program to wrap bridge columns in steel (or fiber-reinforced polymer) casings on older bridges.

Unfortunately, the **1989 Loma Prieta Earthquake** occurred before many bridges were retrofitted. The earthquake damaged the double-deck Cypress Viaduct (33 0178), built in the 1950s, that had been designed with vulnerable pinned connections to make it structurally determinant and easier to analyze. The main reinforcement in these connections was not sufficiently developed, and the shear reinforcement was inadequate. This resulted in the collapse of a mile-long segment of the viaduct during the earthquake. Several other double-deck viaducts around San Francisco sustained severe damage to the superstructure-to-column connections that resulted in their closure and removal after the earthquake. Also, a 50-foot span over Pier 9 on the East Crossing of the San Francisco Oakland Bay Bridge (33 0025), built in the 1930s, collapsed due to inadequate 4-inch-wide seats, reiterating the lesson that seats have to be long enough to support the resulting displaced bridge members during earthquakes. The Struve Slough Bridges (36 0088L/R) in Watsonville were T-girder bridges on piles founded on very soft soil. During the earthquake, the soil shook violently, dragging the piles from their connection with the superstructure which resulted in the pile extensions punching through the bridge deck.

Concerns about the bridge damage prompted the California governor to create a Board of Inquiry that found that Caltrans was doing a good job addressing seismic issues but needed to accelerate the seismic retrofit program. The Board of Inquiry recommended that a standing board of experts should be created to advise Caltrans on its earthquake engineering practices. Thus, the Caltrans Seismic Advisory Board was formed and continues to advise Caltrans on seismic issues. The need to quickly complete the retrofit program was demonstrated again when the **1994 Northridge Earthquake** occurred before the program was completed. Seven bridges, five of which were designed before 1971, were severely damaged during the earthquake but all 60 bridges in the Los Angeles area that had been retrofitted after the Loma Prieta Earthquake performed very well.

I-5: Gavin Canyon Bridge

These two parallel 741-foot-long bridges (53 1797L/R) built in 1955, were designed with table-like center frames that supported the cantilevered spans of the four end frames on highly skewed, 8-inch-long hinge seats. A retrofit in 1974 added restrainers at the hinges. During the earthquake, the outer frames rotated, failing the restrainers, followed by unseating and collapse of the cantilevered spans. In *Figure 1*, the demolition crew has already started removing the bridge before the reconnaissance team could inspect the damage (the team started in Sacramento and were escorted by the California Highway Patrol down I-5 through various detours to a hotel in Pasadena). Among the lessons learned was that the fundamental mode during an earthquake for a bridge may be rotational, not translational; that long seats, not restrainers were needed to prevent unseating; that high skews make it easier for bridges to become unseated by moving normal to the skew; and, that the anchorage for restrainers is often the location of failure. However, most of these lessons had been learned during previous earthquakes. After this earthquake, these bridges were replaced with single frame structures.

Route 14/5 Separation and Overhead

This 1582-foot-long bridge (53 1960F) on single column piers was under construction (and was still on falsework) during the 1971 San Fernando Earthquake, but it collapsed during the Northridge

Earthquake (*Figure 2*). There was considerable speculation as to the cause of the failure, but it was eventually decided (and corroborated by analysis) that it was due to the shear damage to short, stiff Pier 2. Most long bridges have short bents near the ends and tall bents in the middle. As this bridge moved back and forth during the earthquake, the stiffer elements could not displace as much as their taller neighbors and broke. After Pier 2 broke, the superstructure sagged, broke around Pier 3, and slid off Abutment 1 (*Figure 2*) and Pier 4. After the earthquake, Caltrans instituted standards to ensure that the columns within a bent, bents within a frame, and frames in a bridge have similar stiffness or period.

Figure 2. Route 14/5 separation and overhead.

Route 118: Mission Gothic Undercrossing

These parallel structures (53 2205L/R) included a 506-foot-long 3-span left bridge and a 566-foot-long 4-span right bridge on two-column bents and abutments with 4-foot-long seats. The bridges were 98 feet wide with prestressed bent caps (except for Bent 4 on the right bridge). The bridges were designed in 1973 and built in 1976. They crossed over an intersection and consequently had opposing skews at the two ends. The columns were fixed at the top and pinned at the base. A common detail used on these bridges was architectural flares on the columns, which were assumed to spall off during earthquakes. However, during the Northridge earthquake, the flares did not spall off and reduced the effective column height, resulting in a combination of shear and flexural damage. As can be seen in *Figure 3*, the bridges displaced transversely during the earthquake. The right bridge (the left side of *Figure 3*) collapsed while the left bridge settled approximately two feet. Typically, a bridge is locked in by the abutments, which act to limit the movement during earthquakes. It was concluded that having abutments at opposite skews allowed the bridges to move away from the abutments, which contributed to the collapse. After the earthquake, Caltrans funded research at the University of California San Diego, which confirmed the vulnerability of flared columns and a new detail was developed to isolate the flare from the superstructure on new bridges (existing bridges were retrofit with casings around the column and the flare).

Route 118: Bull Creek Canyon Channel Bridge

These parallel 3-span structures (53 2206L/R) were 256 feet long with a variable width (minimum of 200 feet) and a variable skew. Like their neighbor (Mission Gothic Undercrossing), they were designed in 1973 and built in 1976. The bridges were supported on 9 and 10 column bents and tall, end-diaphragm abutments. The columns had a modern design with spirals at a 3-inch pitch at the top and bottom and a 12-inch pitch elsewhere. The bridges crossed over a channel, and the concrete for the channel walls was placed against the columns at Bent 3. The structure appeared to have rotated clockwise during the earthquake. Similar to Mission Gothic, the channel wall had the effect of shortening the columns and consequently attracted more seismic force. Also, the top of the channel wall was where the transverse column reinforcement was at a 12-inch pitch. All the columns at Bent 3 failed in shear (*Figure 4*). The top of some of the columns in Bent 2 formed plastic hinges, probably after the columns in Bent 3 were damaged.

I10: La Cienega-Venice Undercrossing

These parallel, three-frame (7-span) 871-foot-long bridges (53 1609L/R) on 2 and 3 column bents and bin-type abutments were designed in 1962 and built in 1964. The frames were connected with 6-inch-long hinge seats. There was also a connector and an on-ramp on the right bridge. Columns had lapped hoop reinforcement at a 12-inch spacing and were pinned or fixed to pile caps without a top mat or any shear reinforcement. Most of the columns on the right bridge formed plastic hinges at the bottom, although a few columns had plastic hinges at the top (*Figure 5, page 20*). The column damage was thought to have caused Span 6 of the right bridge to become unseated. However, the superstructures were caught by a storage facility that had been built under the bridges. The foundations were excavated after the earthquake, but no damage was found. It was thought that the thick layer of asphalt and concrete pushed the column damage up to where the columns were more vulnerable (although there was a lap splice between the column reinforcement and the footing). An observation after the earthquake was that the columns with

Figure 3. Route 118 Mission Gothic Undercrossing.

Figure 4. Route 118 Bull Creek Canyon Channel Bridge.

Table 1. Incentive/Disincentive Contracts used after the Northridge Earthquake.

Project	Incentive/Disincentive
Santa Monica Freeway (I-10)	$200,000/day
Gavin Canyon (I-5)	$150,000/day
5/14 Interchange	$100,000/day
State Route 118	$50,000/day

42- #11 bar main reinforcing experienced more damage than the columns with less main reinforcement. This bridge was far to the south of the epicenter (which ruptured to the north), but it was felt that long period shaking was amplified by the soft soil (La Cienega is Spanish for "The Swamp").

Lessons Learned

Collectively, the bridge damage described in this article was just a small part of all the damage that occurred during the Northridge Earthquake. A lot of this damage was due to geometric and structural system issues (high bridge skews, unbalanced structures, and non-prismatic members) that resulted in unexpectedly large demands during the earthquake. This gave rise to the development of rules and procedures to ensure that bridge members are well-balanced and that shear-critical members are not used. Large skews are still used on bridges but are mitigated either by eliminating in-span hinges or by very large seats at hinges, abutments, and expansion joints. However, abutments with opposing skews should no longer be used since there is nothing to prevent the bridge from moving away from the abutments, as was seen at Mission Gothic UC.

Procedures, initiated after the Loma Prieta Earthquake, were improved after the Northridge Earthquake. For instance, after Loma Prieta, Caltrans initiated a practice of accelerating earthquake repairs with A+B construction contracts. Caltrans determined the societal cost per day that the bridge/highway segment was not available and contractors bid on the cost + the number of days required to rebuild the bridge. The first A+B contract was to rebuild the Struve Slough Bridges after the Loma Prieta Earthquake. The contractor who was awarded the project had aggressively bid to complete the two parallel 830-foot long slab bridges supported on 200 driven piles in just 90 days. He managed to complete the project in 55 days (by working around the clock) and made a million dollars in incentives.

Due to the success of A+B contracting after the Loma Prieta Earthquake, this type of procurement was used to rebuild all the bridges that collapsed during the Northridge Earthquake. Caltrans economists determined the incentive/disincentive rates based on the projected daily cost for each closed highway (*Table 1*). The Santa Monica Freeway (I-10) was reopened in 3 months. All of the collapsed bridges were reopened to traffic by November 4, 1994 (10 months after the earthquake). While the highways were being repaired, many frontage roads were cleared and converted to High Occupancy Vehicle lanes to alleviate traffic congestion.

The most significant change to seismic design practice after Loma Prieta was that the 'R' factor that had been used to estimate the reduced seismic force in ductile columns was abandoned and a moment-curvature analysis began to be used to determine the *displacement capacity* of substructure members. The columns' effective stiffness was calculated to obtain the period, and the appropriate *design spectrum* was used to get the *displacement demand*. Caltrans was able to update its seismic design procedure after writing XSECTION to obtain the displacement capacity of columns, PSSECTION to obtain the displacement capacity of prestressed piles, and WFRAME to obtain the displacement capacity of bridge frames. Caltrans is continuing to develop the next generation of earthquake engineering tools that will utilize Nonlinear Time History Analysis (NLTHA) procedures for the seismic design of ordinary bridges.

The methods for generating design spectra have also undergone several changes since the Loma Prieta and Northridge earthquakes. Before Loma Prieta, the design spectrum was obtained based on the deterministically-derived Maximum Credible Earthquake of the controlling fault and the depth of alluvium at the bridge site. After the Loma Prieta Earthquake, the shear wave velocity of the soil began to be used for obtaining the design spectrum. After the Northridge Earthquake, it was recognized that near-fault directivity effects increased the demands on long period structures. Response spectra were increased 20% in the long period range for bridges within 10 miles (15 km) from the fault. Also, the envelope of deterministic and probabilistic spectra began to be used to obtain the design spectra for bridges (*Figure 6*).

The most significant change to seismic design practice after the Northridge Earthquake was new rules requiring adjacent columns in a bent and adjacent bents in a frame to have similar stiffness ($k_i/k_j > 0.75$). Moreover, any two bents in a frame and any two columns in a bent were required to have comparable stiffness ($k_i/k_j > 0.50$). The periods of adjacent frames were also required to be similar ($T_i/T_j > 0.7$)

Figure 5. 1-10 La Cienega-Venice Undercrossing.

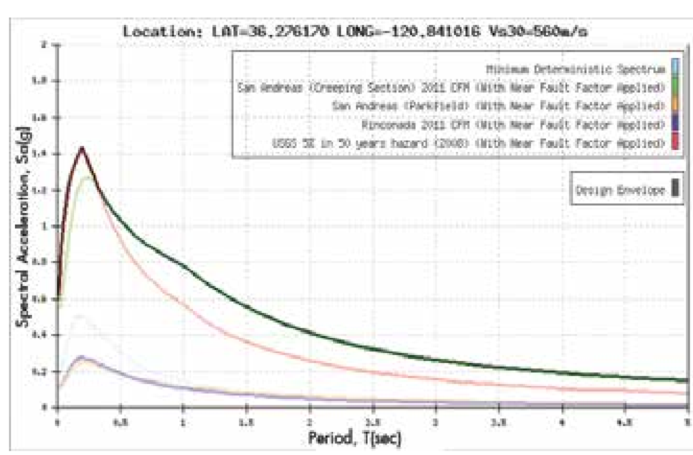

Figure 6. Probabilistic and deterministic spectra with near fault effects and envelope used for design.

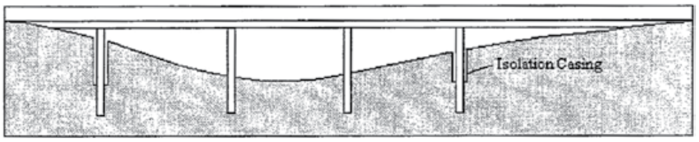

Figure 7. Bridge with isolation casings to achieve a balanced design.

to prevent large out-of-phase movement between frames. All of these rules were to prevent the severe damage that was observed after the Northridge Earthquake. A popular technique that began to be used over uneven terrain was isolation casings to give all the bents about the same stiffness (*Figure 7*).

Other changes after the Northridge Earthquake included:

- Establishment of Caltrans Seismic Design Criteria (SDC) Version 1.0 in 1999 (*now completing Version 2.0*).
- Ground shaking hazards were amplified due to near-fault effects, basin effects, etc.
- Besides the ground shaking hazard, liquefaction hazards, lateral spreading hazards, fault offset hazards, tsunami hazards, and more began to be considered in the seismic design of bridges
- Memo to Designers (MTD) 20-9 provided rules for reinforcement splices in ductile and capacity-protected members.
- New criteria allowed rocking as an earthquake resisting system for existing bridges.
- New criteria were developed for the retrofit of arch, truss, and other non-standard bridges.
- Caltrans began a robust seismic research program and has invested over $100 million since 1989 to better understand earthquake hazards and to develop resilient earthquake resistant bridge systems and details.
- Research showed a smaller role played by vertical acceleration in bridge damage.
- Caltrans required k-rail at the ends of damaged bridges after police drove off several bridges.

Caltrans has not experienced a large, damaging earthquake since Northridge. However, Caltrans engineers and managers are confident that all of the efforts spent developing new seismic design criteria and retrofitting existing bridges will yield less bridge damage during the next design-level earthquake.▪

A critical element was missing before Caltrans could move from a force-based system to a displacement-based approach for the seismic analysis of new and existing bridges. Three structural analysis programs (XSEC, PSS and WFR) were written by Caltrans' bridge engineers to determine the displacement capacity of columns, piles and shafts, and bridge frames. For more information, visit **https://goo.gl/YLjuBh**.

Mark Yashinsky has spent the last 34 years as a bridge engineer at Caltrans and has worked in the Caltrans Office of Earthquake Engineering since the Loma Prieta Earthquake. Among his many duties is leading the post-earthquake inspection team, developing new seismic criteria, and managing the seismic retrofit program. He has written a number of books, papers, and articles on bridges and earthquakes. (mark.yashinsky@dot.ca.gov)