Evolution of the Caltrans *Seismic Design Criteria*

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Figure 1. Bridge damage from the 1971 San Fernando earthquake. All Photos and Figures: California Department of Transportation.

California's bridge inventory is mainly composed of cast-in-place and precast concrete structures. Of the 25,000 state and local agency bridges in California, about 88% are made of concrete. California's bridge inventory can be categorized by expected seismic performance. "Important bridges" are expected to provide immediate access to emergency facilities after an earthquake. "Recovery bridges" serve as vital links for rebuilding damaged areas shortly after earthquakes and should be available for public use a few days after a seismic event. All other bridges are designated as "ordinary bridges," which comprise 99% of California's bridge inventory.

Three damaging earthquakes, the 1971 San Fernando earthquake, the 1989 Loma Prieta earthquake, and the 1994 Northridge earthquake, were the impetus for California's bridge seismic safety program. The San Fernando earthquake caused the collapse of five bridges (**Fig. 1**) and the death of two people. The Loma Prieta earthquake caused the collapse of one span of the San Francisco–Oakland Bay Bridge and a one-mile segment of the Cypress Street Viaduct in Oakland, resulting in the death of 43 people. The Northridge earthquake resulted in the collapse of seven bridges and one death. These damaging earthquakes spurred the California Department of Transportation (Caltrans) to focus on life safety by minimizing the probability of a bridge collapse during earthquakes.

The modern history of seismic design began after the 1933 Long Beach earthquake and the passing of the Field Act, which required California to design schools for seismic hazards. California's Division of Highways (now Caltrans) followed the state's lead by requiring bridges to be designed for a horizontal coefficient of 0.06 times the weight of the structure. At the time, California was the only state addressing seismic hazards.

In the aftermath of the 1971 San Fernando earthquake, engineers began increasing bridge column strength to resist ground shaking hazards. However, they soon discovered that adding strength increased the bridge's stiffness, which in turn increased the seismic demands on the bridge. **Figure 2** illustrates how the initial stiffness determines the structure's period and the load it attracts during strong ground shaking.

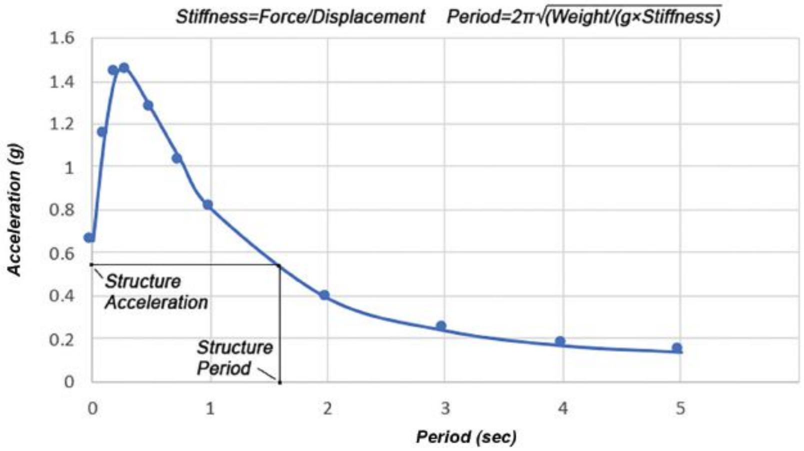

Figure 2. Typical Caltrans response spectrum for bridge design. The initial stiffness of a structure determines its period and the load it attracts during strong ground shaking.

In the mid-1970s, Caltrans began adopting the principles of ductile design of reinforced concrete columns developed by John Blume—cofounder of Earthquake Engineering Research Institute and recognized as the "father of earthquake engineering"—and capacity-protected design, in which the members adjacent to the ductile columns are designed to be stronger than the columns to ensure all damage occurs in the ductile element, developed by Robert Park and Tom Paulay. These principles provided the basis for ductile column design and strong connecting elements that formed the Caltrans seismic design philosophy for concrete bridges.

The geometry and component design of concrete beam and girder bridges lent themselves to incorporating fuses and capacity-protected elements by increasing the transverse reinforcement in columns and shafts and fusing abutment shear keys and backwalls. However, accurately determining earthquake demands and structure capacities turned out to be a more difficult task.

After the San Fernando earthquake, Caltrans adopted elastic-dynamic analysis for estimating the inelastic displacement demands for bridges. This was based on Nathan Newmark's observation that long-period linear and nonlinear systems with the same initial period would have about the same maximum displacement for a given ground motion. This design philosophy was used to address the inelastic demands imposed by a large earthquake on a structure with proper structural detailing. The large moments and shear forces obtained from the elastic analysis were reduced by *Z* factors to obtain the inelastic moments and shear forces on the structure (**Fig. 3**). This method of design and analysis is still allowed in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] and is often referred to as the "force method."

During the 1970s, Caltrans adopted a response spectrum analysis to determine the seismic demand on bridges based on the factors *A*, *R*, and *S*. A response spectrum is a plot of the maximum response (acceleration, velocity, or displacement) of single degree-of-freedom systems having different natural periods that are all excited by the same base motion. The *A* factor was the peak rock acceleration obtained from seismic hazard maps, and *R* was the normalized 5%-damped rock spectra response factor. By multiplying *A* by *R*, an elastic spectrum for rock was obtained. The rock motion was converted to a soil spectrum by multiplying the spectrum by an *S* factor. The product of these three factors obtained at different periods provided a smooth, elastic, 5%-damped response spectrum at any bridge site (Fig. 2). However, these spectra were based on a deterministic "maximum credible earthquake" of each fault. The adoption of probabilistic response spectra, which addressed the likelihood of larger earthquakes over longer time periods, by AASHTO and later Caltrans took another 20 years.

Caltrans's first *Seismic Design Criteria* (SDC) was published in 1973. **Figure 4** is reproduced from that publication and shows the elastic force reduction due to the nonlinear response for bridge columns, abutments, and restrainers.

After the Loma Prieta earthquake, Caltrans began retrofitting its vulnerable bridges for seismic events. However, researchers and bridge engineers realized that better tools that incorporated nonlinear capacities of bridge elements were needed. At the University of California–San Diego, Nigel Priestley and Frieder Seible pioneered column and cased-column testing and new tools for capturing the post-elastic concrete column response that contributed greatly to the success of the seismic retrofit program.

Caltrans engineer Mark Mahan developed software to obtain moment and deformation capacities of new and retrofitted columns and shafts and "pushover" software that generated the displacement capacities of bridge frames. In 1999, Caltrans adopted displacement-based design principles for all bridges.[2] However, it would take many years before Caltrans developed procedures to reliably obtain the inelastic displacement demands for ordinary bridges.

The Northridge earthquake showed engineers that large variations in superstructure mass and substructure stiffness in adjacent elements, such as variations in columns of a bent, bents of a frame, or frames of a bridge, increased earthquake damage. Shortly after Northridge, Caltrans required that the stiffnesses of columns and bents be balanced to prevent damage to stiffer elements during strong shaking.

After the Northridge earthquake, Caltrans also developed "ARS Online," which allowed engineers to obtain both probabilistic and deterministic ground motions for any bridge site in California. Although AASHTO adopted probabilistic seismic hazards in 1994, it wasn't until 2009 that Caltrans adopted probabilistic spectra. At that time, Caltrans started using the larger of deterministic and probabilistic ground shaking spectra;

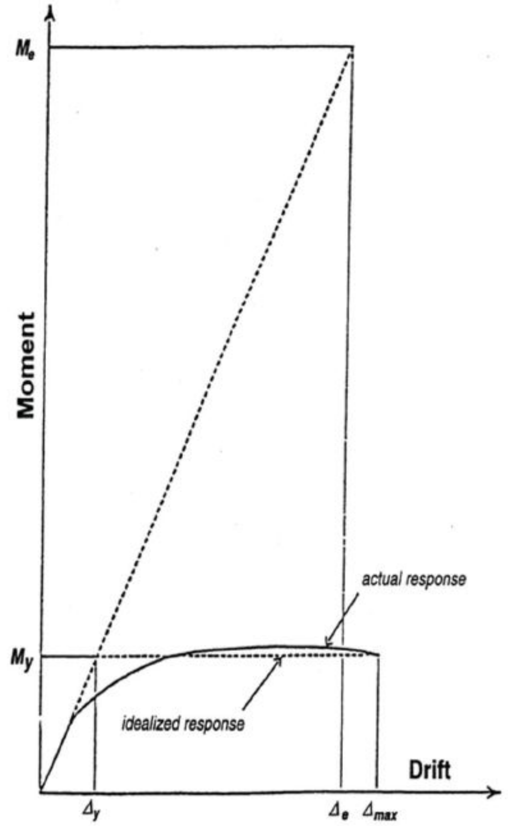

Figure 3. Moment *M* compared with drift Δ for a typical bridge element showing the theoretical elastic and the actual behavior. The *Z* factor was defined as the reduction of the seismic moment (or force) due to the nonlinear response of the bridge: $Z \approx M_e/M_y$.

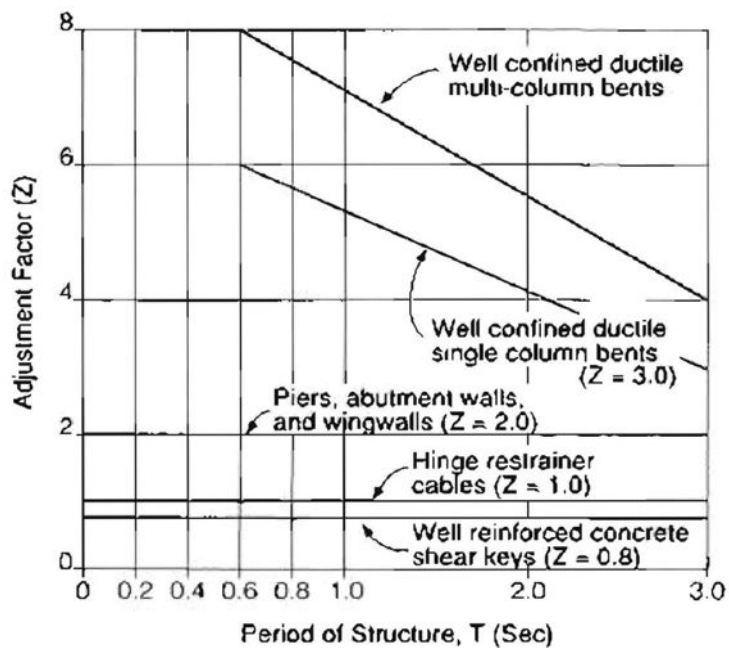

Figure 4. *Z* factor chart for different types of elements from the 1973 Caltrans *Seismic Design Criteria*.

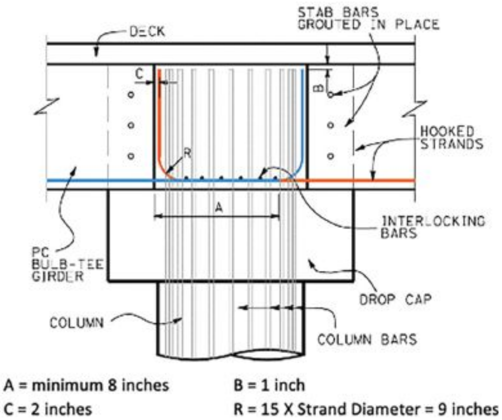

Figure 5. Draft details from Caltrans for accelerated bridge construction of a precast concrete girder–to–bent cap connection using extended, hooked strands for continuity.

eventually, after finding that probabilistic spectra controlled in active seismic regions, Caltrans abandoned the use of deterministic ground shaking spectra. These probabilistic spectra allowed Caltrans to begin using probabilistically derived (through spectral matching) suites of time histories that could be used to analyze nonlinear bridge models. In addition, Caltrans also started using other probabilistically derived seismic hazards such as fault offsets. Adopting probabilistic seismic hazards enabled Caltrans to develop guidance and tools for performing nonlinear time history analyses for typical bridges.

Rather than always relying on column plastic hinges as the earthquake-resisting element on bridges, Caltrans developed criteria for isolation devices, damping devices, and rocking foundations. These alternative earthquake-resisting elements had been used for retrofits but are now being applied to the design of new bridges.

In support of the accelerated bridge construction initiative, Caltrans has developed a suite of capacity-protected details for precast concrete girders to ensure the inelastic behavior is limited to the ductile column elements (**Fig. 5**).

Caltrans has incorporated several other hazards into the current version of its SDC,[3] including probabilistic methods for determining the fault offset and tsunami hazard along the coast. Updated rules for designing bridges for liquefaction and lateral spreading are being tested on new bridges and the retrofit of existing bridges. Because Caltrans bridges will be tested during large future earthquakes, the SDC will likely continue to evolve.

The greatest lesson learned from the three momentous California earthquakes is that bridge engineers will never be done improving the seismic resiliency and safety of our bridges through research and innovation. As aptly stated by the late Joseph Penzien, chairman of the Caltrans Seismic Advisory Board, "Earthquakes measure our actions, not our words."

References

1. American Association of State Highway and Transportation Officials (AASHTO). 2020. *AASHTO LRFD Bridge Design Specifications*. 9th ed. Washington, DC: AASHTO.
2. California Department of Transportation (Caltrans). 1999. *Seismic Design Criteria*. Version 1.1. Sacramento, CA: Caltrans.
3. Caltrans. 2019. *Seismic Design Criteria*. Version 2.0. Sacramento, CA: Caltrans.