CALTRANS EVOLVING SEISMIC DESIGN PRACTICE

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ABSTRACT

There are over 12,000 bridges on the state highway system in California. These bridges must be designed to resist seismic hazards endemic to the region. From the time just prior to the 1971 San Fernando Earthquake to today, significant change has taken place in the way in which bridges are designed to resist these seismic hazards. This paper looks at lessons learned from past significant earthquakes, the development of strategies to improve bridge performance through problem-focused research, and the advances in bridge seismic design and retrofit standards that have been made over the past nearly forty years. Finally, it looks ahead at future plans to partner with academia, national and international bridge professionals, and both bridge and non-bridge industries to further improve bridge seismic performance through the use of new materials, systems, construction methods and other means.

LESSONS LEARNED IN PAST EARTHQUAKES

San Fernando Earthquake

The current era of Caltrans seismic design practice began essentially with lessons learned from the 1971 San Fernando Earthquake. This devastating temblor, which occurred on February 9, 1971 resulted in damage to bridge structures from Missions Hills to the south, northerly and easterly through San Fernando, with collapse of structures at the Route 210/Interstate 5 and Route 14/Interstate 5 highway interchanges. Caltrans instituted the use of a Post-Earthquake Investigation Team (PEQIT) to investigate the damage, a practice that continues today. Their conclusions included:

- Minimize the number of in-span thermal expansion joints, and where hinges are used, ensure there is ample seat width.
- The earthquake forces of the San Fernando Earthquake greatly exceeded the earthquake forces required by the design specifications.
- Tall slender columns performed better than short stiff columns
- The number of column ties should be increased at the points of highest stress and use of spirally reinforced columns or cores should be encouraged, i.e. improve confinement details.
- The earthquake design criteria and methods of analysis should be reviewed.

In February of 1971, Caltrans released a new “Memo-to-Designers” modifying its design standards to increase the amount of transverse column reinforcement and required the inclusion of a top mat of reinforcement in footings and pile caps. In addition, details were provided to add hinge restrainers to existing hinge seats, and hinge seat lengths were increased to minimize the risk of unseating. These new details were to be applied to all new designs and incorporated into bridges under construction. In 1973, Caltrans worked with the California Division of Mines & Geology (since renamed California Geological Survey) to develop a statewide fault map and began designing for ground

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motion accelerations tied to bridge site location. In order to address what was seen as the most serious seismic vulnerability, Caltrans embarked on a seismic retrofit program to install cable hinge restrainers to limit the risk of superstructure unseating. Caltrans seismic design specifications were updated again following the publication of the results of ATC-6 by the Applied Technology Council in 1981.

FIGURE 1: SAN FERNANDO EARTHQUAKE DAMAGE

Whittier Narrows Earthquake

Early in 1987, Caltrans began the column retrofit seismic research program in an effort to develop methods to retrofit existing single column bents. As this research progressed, on October 1, 1987, the Magnitude 6.0 Whittier Narrows earthquake shook the Los Angeles area, causing significant shear damage to the I-605/I-5 Separation. This reinforced recognition of the potential vulnerability of bridges designed using the seismic design criteria in place prior to changes made following the San Fernando earthquake. This research ultimately led to the use of steel shells placed around existing columns to provide confinement and increase both column ductility and shear capacity. Based on this research, Caltrans began developing contract plans to retrofit bridges with single column bents. Additionally, during this period Caltrans continued the process of retrofitting over 1000 bridges with restrainer cables to resist collapse due to unseating at hinges and bent supports. The cable restrainer retrofit phase was completed in 1989 at a cost of more than $50 million.

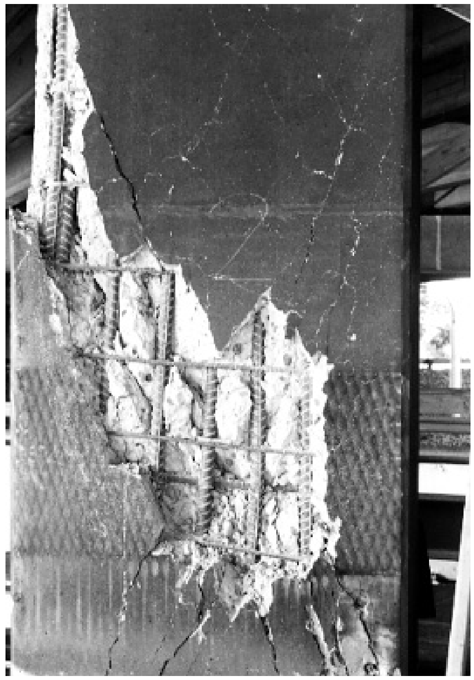

FIGURE 2: WHITTIER NARROWS EARTHQUAKE DAMAGE

Loma Prieta Earthquake

On October 17, 1989 the Magnitude 7.1 Loma Prieta earthquake hit the San Francisco Bay Area, which resulted in the collapse of one span of the East Spans of the San Francisco – Oakland Bay Bridge on I-80, portions of the double-deck Cypress Viaduct structure on I-880 in Oakland, and the Struve Slough Bridge on Highway 101. Other double-deck structures including the I-280 Souther Viaduct suffered significant joint damage, but did not collapse. Also clearly demonstrated in this earthquake were the effects of local site conditions. Much of the damage occurred at sites with deep cohesive soils where ground shaking was amplified, resulting in increased displacements of structures with longer periods. Bridges that had been retrofitted with cable restrainers during the initial phase of Caltrans Seismic Retrofit Program performed well. However in light of the column and joint damage that occurred, funds for the column seismic retrofit program, including those for research and construction, were increased substantially. Based on the seismic retrofit designs underway prior to the Loma Prieta Earthquake, the first column retrofit projects were advertised in January 1990.

FIGURE 3: LOMA PRIETA EARTHQUAKE DAMAGE

Northridge Earthquake

In the midst of the ongoing column seismic retrofit program, on January 17, 1994 the Magnitude 6.7 Northridge Earthquake occurred in the same general location as the 1971 San Fernando Earthquake in southern California. Five bridges collapsed and an additional four bridges had major damage as defined in "The Northridge Earthquake Post-Earthquake Investigation Report". Bridges designed to modern standards and those that had been seismically retrofitted performed well. Damage to bridges with irregularities in their configuration, including large skews, short columns mixed with longer columns, and columns with architectural flares pointed out how geometric effects could affect bridge performance. As a result design innovations were developed during the subsequent rebuild of damaged or collapsed structures including the use of double-cantilever seatless hinges, isolation wells to extend the effective length of short columns.

FIGURE 4: NORTHRIDGE EARTHQUAKE DAMAGE

DEVELOPMENT OF CALTRANS SEISMIC DESIGN CRITERIA

Prior to the San Fernando earthquake only rudimentary consideration was given to designing bridges for earthquake ground motions. The lateral earthquake loading specified in the AASHTO Standard Specifications for Highway Bridges prior to the San Fernando earthquake used a simple force based equation:

$$EQ = CD$$

where C varied from 2% to 6% of gravity depending on the foundation type.

In 1975 the Federal Highway Administration contracted with the Applied Technology Council to develop updated seismic bridge design specifications, resulting in the publication of ATC-6 in 1981. Force design methods were used in which structures were analyzed elastically, and seismic forces were reduced for ductility and risk by a reduction factor, Z, which varied based on the structure's period and redundancy of the component. Elastic loads were determined based on one of a set of four standard acceleration response spectra, which were dependent on soil conditions at the bridge site. Typically bridges were analyzed using three-dimensional elastic dynamic multi-modal analysis. The flexural capacity of the columns were designed for these elastic seismic loads, reduced by Z, and the designer ensured minimum prescribed transverse reinforcement requirements were met.

While a marked improvement over past practices, the force design method did not explicitly consider the ductility capacity or demand expected at each plastic hinge. Instead the force reduction factor used to reduce the reported elastic forces was based on an assumed or expected ductility for typical structures designed with levels of transverse reinforcement and the accompanying provisions required by the Caltrans Bridge Design Specifications. Thus variations in ductility based on transverse confinement, geometry, strength and stiffness of adjacent components, foundation flexibility, column aspect ratios, fixity conditions, or other factors which are known to impact the actual capacity of a structure were not explicitly considered. Nor were the expected locations of plastic hinges verified by considering relative strengths of components meeting at joints. Thus it was possible for understrength nonductile components adjacent to columns to reach their capacity prior to columns, with their ductile details, from reaching their elastic limit. Because capacity design principles were not used, unrealistic loads were indicated in nonductile members intended to either remain elastic, such as girders, bent caps, and foundations or to fuse as sacrificial elements including the abutment backwalls, wingwalls, and shear keys.

The seismic design criteria initially used for the column seismic retrofit program was based on this same force design method. However, Caltrans was able to take advantage of the focused seismic retrofit research program and began incorporating the results on seismic retrofit projects, sometimes before the final research report was even published. A substantial design shift occurred with the adoption of displacement design methods outlined in Report No. SSRP 91/03, Seismic Assessment and Retrofit of Bridges by the University of California, San Diego. Use of displacement ductility methods were used initially for the retrofit of the Santa Monica Viaduct on Route 10 in Los Angeles, which was being retrofitted as part of Caltrans Seismic Retrofit program. Use of displacement design methods were incorporated into other seismic retrofit projects on a case by case basis, and ultimately became the de facto seismic retrofit design methodology.

As familiarity and use of displacement ductility methods grew during the decade following the Loma Prieta Earthquake, Caltrans design philosophy and accompanying criteria evolved. A team was formed and the new methodology was documented with the December 1999 publications of the new displacement based Caltrans Seismic Design Criteria (SDC). The philosophy of the SDC is to design structures incorporating the following elements:

- Displacement based methodology
- Adequate confinement to ensure ductile response of columns
- Capacity protection of the superstructure and foundation to force plastic hinging into the well confined ductile columns
- Balanced geometry and mass/stiffness compatibility to share seismic protection amongst the ductile columns and avoid the concentration of damage in just a few locations.
- Encourage redundancy such that the overall bridge system performs well even if an individual component may be significantly damaged
- Adequate support length to accommodate anticipated displacements

These provisions incorporated results published in ATC-32 and NCHRP 12-49, results of Caltrans seismic research program, and design practices developed through the experiences of the Seismic Retrofit Program.

CALTRANS SEISMIC RETROFIT PROGRAM

Caltrans Seismic Retrofit Program is nearly complete with six of seven bridges in the Toll Seismic Retrofit Program completed and construction ongoing on the last, the replacement of the East Spans of the San Francisco-Oakland Bay Bridge. In addition, the non-Toll seismic retrofit program is over 99% complete, with only five bridges remaining to be retrofitted on the state highway system. The Local Seismic Safety Retrofit Program, which covers local agency bridges in California that are not on the state highway system, received an influx of funding with the passage of Proposition 1B in November, 2006. Currently 765 of 1235 local agency bridges have been retrofitted, with another many of the remaining bridges currently in the design phase. Upon completion of the seismic retrofit of bridges in California, substantial improvements will have been made to protect the traveling public by meeting "no collapse" life safety performance. The expected performance has been summarized by Caltrans independent external Seismic Advisory Board, which states in its December 2003 report, *The Race to Seismic Safety*, that "*Following a large earthquake the SAB expects that many Standard bridges near the epicenter will be sufficiently damaged as to be out of service for a period of time, and some may require replacement. Collapse is not expected for most of these bridges, but repair for some may not be economical*." Thus the investment of billions of dollars in seismic retrofit has addressed life safety needs, however it is clear that not all bridges will remain open after a large earthquake. As has been seen in past earthquakes, bridge closure can have substantial impacts on the transportation network, resulting in reduced traffic capacity and associated detrimental economic and social effects.

FIGURE 5: COLUMN RETROFIT USING STEEL CASINGS

NEXT GENERATION OF CALIFORNIA BRIDGES

While it may not be cost effective to retrofit most bridges to a higher level of post-earthquake performance, recent studies and research indicate that it may be possible to design new bridges to provide some level of post-earthquake serviceability. The question therefore is what seismic performance level goals should be established for future bridges, and on which bridges should an investment in improved earthquake performance be made? In order to answer this question, a number of issues must be considered. The costs of building bridges with improved post-earthquake serviceability must be weighed against the probability of a damaging earthquake occurring, leading to the economic and social costs of bridge closure. If new bridge systems, components or devices are developed to improve earthquake performance, durability and reliability issues must be addressed. Bridges have a useful life of 50 to 100 years or more. Seismic devices used to improve bridge performance may be in place for decades before being called upon to resist significant earthquake ground motions. Methods must be available to inspect and verify these devices will perform as designed. The costs of maintaining, inspecting, and replacing devices as needed must be considered against the possibility of incurring the costs of bridge closure in an earthquake.

In developing the next generation of California bridges, there is another major consideration, the development of bridge systems capable of accelerating bridge construction (ABC) to reduce the impacts of bridge work on traffic. With the focus on improved post-earthquake serviceability and the development of accelerated bridge construction techniques, it is clear that the consideration of the economic impacts of traffic disruption are having a profound effect on the way Caltrans bridge design practices in the future. In order to reach this goal, a number of steps are underway in the development of the next generation of California bridges, with the discussion of these steps to follow.

The Federal Highway Administration has been pushing the concept of "Get in, get out and stay out" and has been advocating accelerated bridge construction techniques. However, methods that have been used successfully in other areas of the country are not necessarily appropriate for use in moderate to high seismic regions like California. At the annual Transportation Research Board (TRB) meeting in January of 2007, California representatives agreed to take the lead in developing ABC techniques that addressed seismic issues. A workshop was organized by TRB, FHWA and Caltrans and held in October 2007 in San Diego, California. Representatives from several state DOT's, FHWA, TRB, researchers, and industry met, leading to the publication of the document, " 2007 FHWA Seismic Accelerated Bridge Construction Workshop Outcomes and Follow-up Activities". As the title this publication implies, the workshop resulted in the development of an Action Plan to guide future Seismic ABC activities. A follow-up meeting was held at the January 2008 TRB meeting, resulting in the development of three Seismic ABC related research problem statements. In California, a Seismic ABC Work Team was created to focus efforts for application by Caltrans. In July 2008 this team published "Accelerated Bridge Construction Applications in California – A Lessons Learned Report", documenting recent use of ABC techniques in California. This includes emergency recovery efforts following the unplanned closure of major transportation arteries following recent fires at both the MacArthur Maze approaching the San Francisco-Oakland Bay Bridge, and at the Route 14/Interstate 5 Truck tunnel, and for planned work including the the Labor Day weekend closure of I-80 at the Bay Bridge to demolish and roll in a new bridge in mere days. The report also documents the use of precast concrete technology on several projects to reduce working days and traffic impacts. However to fully implement ABC methods, remaining seismic issues must be resolved, particularly the development and testing of connection details capable of resisting seismic loads and deformations.

FIGURE 5: PRECAST BENT CAP TO COLUMN CONNECTION

The Federal Highway Adminstration has embarked on a multi-million dollar project through the University of Nevada, Reno to look at ways to increase the resilience of transportation networks. As part of this project, FHWA's earthquake loss estimation software tool called REDARS (Risks from Earthquke Damage to Roadway System) will be updated to improve its accuracy in predicting bridge damage and associated costs, and increase its flexibility for wider application. As REDARS becomes more fully developed, it may be used to identify the costs of bridge closure due to increased congestion and traffic delays, allowing transportation agencies to assess the costs and benefits of designing bridges with improved post-earthquake serviceability.

In order to develop ideas for the next generation of California bridges to meet the goals of accelerating bridge construction as well as providing for improved post-earthquake serviceability, Caltrans is planning a two day workshop being organized under contract with UC-Berkeley in late 2008 or early 2009. In preparation for this workshop, members of Caltrans Earthquake Committee and Seismic ABC Work Team have been called upon to brainstorm and recommend bridge components, devices and systems that are most promising for deployment by Caltrans for discussion at the workshop. While these ideas are still under development, the following ideas are expected to be considered and explored further:

- Precast bridge components emulating the performance of cast-in-place structures
- Connection details and components capable of resisting seismic deformations
- Unbonded prestressed columns with recentering characteristics
- Precast segmental columns with energy absorbing joints
- Seismic protection devices including bearings, dampers, and lock-up devices
- Rocking bridge foundations

- Replaceable bridge components including column plastic hinge regions, shear links and link beams
- Concrete filled tubes including steel and FRP composites
- Disconnected spread footing foundations on poor soils using piles or soil improvement techniques
- Advanced materials including high strength concrete, rebar and steel, shape memory alloys, fiber reinforced engineered cementious concrete, fiber reinforced polymer composites, etc.
- Use of fiber-reinforced polymer to rapidly repair column plastic hinge zones
- Rapid post-earthquake bridge assessment using seismic instrumentation

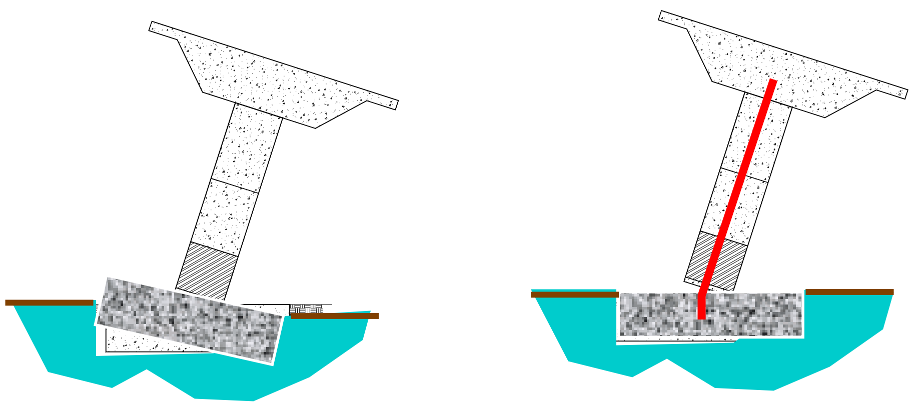

FIGURE 6: ROCKING FOUNDATION AND POST-TENSIONED COLUMN
(Courtesy of UC-Berkeley)

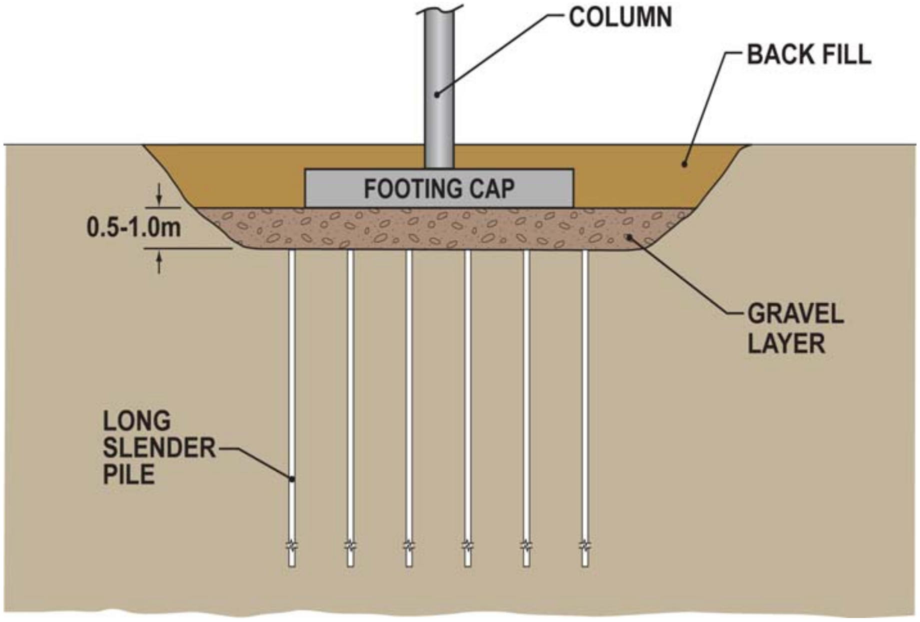

FIGURE 7: DISCONNECTED SPREAD FOOTING
(Courtesy of CH2Mhill)

Whatever systems, devices or components are developed in the upcoming workshop, each will have be evaluated to consider:

- Post-earthquake serviceability
- Post-earthquake repairability
- Traffic impacts
- Life cycle costs
- Constructability
- Maintenance requirements
- Durability
- Reliability
- Ease of future widening and other modifications

Following the workshop, a program of research will be developed to investigate the most promising ideas. As these ideas mature they will be incorporated into pilot projects, appropriate design specifications and guidance material will be developed, and standard details developed.

CONCLUSION

Caltrans has made significant strides in responding to the painful lessons learned from past earthquakes. The Seismic Retrofit Program is nearing completion, with the use of cable restrainers, column casings and other methods to limit the risk of collapse of existing bridges in future earthquakes. It has initiated and continued to fund an ongoing seismic research program to continue to improve its understanding of bridge performance to resist seismic hazards. A displacement based seismic design philosophy has been adopted to ensure ductile behavior of bridges pushed beyond elastic limits by ground motions. Now, looking ahead, Caltrans seeks to not only ensure bridges meet life safety needs, but consider the development of the next generation of bridges capable of providing post-earthquake serviceability, leading to a resilient transportation network that recovers quickly after a major earthquake. There is much work to be done, but if the goal of developing cost-effective, reliable methods of improving post-earthquake performance of ordinary standard bridges is realized, the payoff will be substantial.

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