Recent Changes to Seismic Design Practice in California

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Abstract

Caltrans Seismic Design Criteria requires bridges to have columns that can form plastic hinges and that have sufficient ductility for even unexpectedly large earthquakes. Most of these bridges are cast-in-place, post-tensioned box girder structures with integral bent caps. Caltrans engineers have been working to make other types of bridges conform to the same seismic criteria. Designing for other seismic hazards, improving analysis procedures, developing new retrofit procedures, better reinforcement details, and developing criteria for earthquake resistant elements other than ductile columns have been the source of considerable effort on the part of Caltrans Office of Earthquake Engineering in recent years.

Introduction

The typical bridge in California is a monolithic, cast-in-place, post-tensioned box girder structure. This type of bridge came to dominate California's highways as contractors accumulated formwork and as Caltrans developed experience and confidence in this kind of bridge. Caltrans' Seismic Design Criteria (SDC) (Caltrans, 2013) with its emphasis on columns that form plastic hinges is due to Caltrans large inventory of monolithically constructed bridges with moment resisting frames.

However, this type of bridge may be on its way out in California. There is a push by the Federal Highway Administration (FHWA) for Accelerated Bridge Construction (ABC) and the Next Generation of Bridges (NGB) to speed bridge construction without disrupting existing traffic. Also researchers are testing bridges that can remain relatively undamaged and can be put back into service soon after an earthquake. Caltrans Office of Earthquake Engineering (OEE) is helping to write the AASHTO Seismic Guide (AASHTO, 2011) for the use of other states with its emphasis on other types of bridges. It may be convenient to eventually adopt this Guide in California. All of these influences may eventually change California's inventory of bridges with accompanying changes to Caltrans SDC.

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CHANGES TO BRIDGE CONNECTIONS

Fixed Connections

Much effort has been spent on designing strong reliable connections between bridge members. Caltrans philosophy of capacity-protection relies on fixed column connections that won't be damaged by joint shear due to column plastic hinging. The current joint shear criterion requires the engineer to determine the principal stresses in the joint. If the stresses are low than just some additional reinforcement is required but if the stresses are high the joint must be made larger. Confinement reinforcement must continue from the column to the top mat of reinforcement in the bent cap and the bottom mat in the pile cap. The main column reinforcement must be fully developed into the top and bottom joints. This can be a problem since large diameter reinforcement requires deep caps to fully develop. The use of 'T' headed main reinforcement, dropped bent caps, or smaller diameter longitudinal reinforcement would be required for joints with a small depth.

Pinned Connections

Caltrans prefers fixed connections for bridge columns but sometimes a pinned connection is required. Caltrans uses pins for outrigger bent connections. A pin may also be required if the column diameter is bigger than the superstructure depth. Multicolumn bents have pinned connections at the bottom of the columns to reduce the size of foundations, a major cost for bridges. Reliable pinned connections that can handle service loads and aren't damaged by earthquakes are a subject of continuing research at UN Reno (Saiidi, 2010). Poorly designed pins resulted in the collapse of a mile long section of the Cypress Viaduct during the 1989 Loma Prieta Earthquake. Caltrans uses pipe pins and reduced section reinforcement pins to connect columns to caps. The pins typically require some kind of replaceable bearing surface and adequate transverse reinforcement to protect the concrete around the pin.

Splices

Caltrans has strict rules about the use of reinforcement splices. No splices are allowed in plastic hinge zones (PHZ) and only pre-approved ultimate splices can be used outside the PHZ of ductile members. Most capacity-protected members require ultimate splices while the reinforcement for remaining portions of the bridge can have a service or lap splice. Caltrans seldom uses spiral reinforcement in columns anymore, but when they do the spiral splice must be an extra 180° lap with a diagonal hook through the concrete core. Most columns use hoops, which require an ultimate splice. Caltrans seismic philosophy relies on an abundance of continuity and development to hold things together during earthquakes. Unfortunately, reinforcement typically comes in 60 ft (18 m) lengths. Therefore rules about ‘no splices’ sometimes require exceptions for long or tall bridges.

Seats

The superstructure to substructure connection at abutments and bents is often a seat. Caltrans will sometimes eliminate the seat in favor of end-diaphragm abutments and integral bent caps, especially in regions of high seismicity. However, very long bridges usually require an in-span hinge seat to accommodate temperature, prestressed shortening, and other longitudinal displacements. Caltrans requires these seats to be longer than the Square Root Sum of the Squares (SRSS) of the displacements of the adjacent frames (plus creep, shrinkage, etc.) but not less than 24 inches (600 mm). Shear keys are provided at the left and right ends of abutment and bent cap seats to prevent transverse displacement (and bearing damage) from smaller earthquakes. Recent research (Bozorgzadeh, 2007) has shown these shear keys are stronger than anticipated and so a new modular shear key has been designed that will fail before more important bridge members can be damaged. For in-span hinge seats, double strong steel pipes are sometimes placed through the joint to prevent transverse movement and to provide a longer seat.

CHANGES TO BRIDGE MEMBERS

Foundations

At the bottom of a column is a spread footing, a pile cap, or large diameter shaft. Caltrans uses two kinds of shafts to support bridge columns. A Type 1 shaft is about the same diameter as the column and is designed to form a plastic hinge below the ground surface. Caltrans likes Type 1 Shafts because of their high ductility and long plastic hinge length. Testing at UCLA (Wallace, 2001) showed a 1.8 m (6 ft) diameter shaft had a 20% drift ratio. A Type 2 shaft has a larger diameter than the column to form a reliable plastic hinge above the ground.

The construction of shafts can be difficult and rules for construction and for earthquakes are sometimes in conflict and have to be resolved. For instance, the column reinforcement developed into the Type 2 Shaft should be as short as possible to make it easier for Construction to put a cold joint in the shaft that doesn’t require special safety equipment for workers going down into the hole to clean the joint. Currently testing is being done at UC San Diego (Shing, 2012) to determine the bond-slip behavior of these large-diameter bars. This is the first time that very large diameter rebar has been tested and special equipment was needed to provide the pull-out force and special details were need to securely grab the rebar. Construction would also like to maintain a five-inch (130 mm) window between longitudinal and transverse reinforcement in a shaft for the effective flow of wet concrete. Also, construction requires at least two PVC pipes in the shaft to check for anomalies in the concrete. This can interfere with a rule for less than eight inches between the main reinforcement. It’s hard to make a shaft that meets all of these requirements. Also, Construction doesn't like to pour shafts in wet conditions. This has made the use of large diameter Cast in Steel Shell (CISS) shafts much more popular.

The design of foundations depends on soil conditions and requires good communication between the geotechnical and the bridge engineer. Caltrans formed a committee to study the behavior of pile groups in competent and poor soil. They found that in good soil, the piles were essentially axial members and inexpensive standard piles could be used with pinned connections. However, in poor soil the piles must be have good ductility and fixed connections to the pile cap.

Spread footings are allowed to support abutments and bents on good material in areas of low to moderate ground shaking. Designers sometimes attach tie downs to spread footings to prevent overturning during earthquakes. Recent research (Deng, 2010) suggests that these spread footings could be allowed to rock, even for very large earthquakes (see section on EREs). However, there is a natural hesitancy to allow a bridge to rock back and forth. One can only too readily imagine the bridge rocking over.

Substructures

Caltrans prefers flexible columns to rigid pier walls, but they still allow them to be built. The SDC philosophy of plastic hinge elements and capacity-protected adjacent elements cannot be followed with pier walls, which are stronger than the foundation and can’t form a plastic hinge in the transverse direction. Caltrans requires pier walls to be designed as shear elements for the peak spectral acceleration of the Design Spectrum (times a safety factor). Pier walls are reinforced with stirrups and ties that can come loose during a large earthquake. Caltrans requires a cross tie with alternating 135 degree hooks at one end and 90 degree hooks at the other end wherever vertical and horizontal bars come together in a pier wall.

CHANGES TO TYPES OF BRIDGES

Caltrans is working to make more types of bridges fit the classification of ‘Ordinary Standard Bridge’ that can be designed using the SDC.

Slab Bridges

Slab bridges are designed using charts that had been recently updated for Load and Resistance Factor Design (LRFD). The charts provide the slab depth, reinforcement details, and pile spacing based on span length. Slab bridges are easy to design and cheap to build and so there is some reluctance to change the design to make them meet the requirements in Caltrans SDC. However, research at UN-Reno (Sanders, 2009) showed that well-designed piles with a fixed connection could result in joint shear damage in the slab. Also, the standard piles/shafts used to support the slab used wire for transverse reinforcement that can't form a plastic hinge with sufficient ductility. Caltrans formed a subcommittee, which is trying to develop a seismic design procedure that retains the use of the existing design charts (except in areas of very high seismicity). However, there is not a lot of slab reinforcement to meet the capacity-design requirements in the SDC.

The new criteria would require the columns (shaft/pile extensions) that support slab bridges to be at least 0.5 meters (18 inches) in diameter and have #13 metric (#4 US) hoops/spiral reinforcement. There are (at least) four ways for slab bridges to meet the requirements in Caltrans SDC with the stronger, more ductile columns.

1. Increase the slab depth until slab capacity overcomes top of column capacity.
2. Create a reduced column section between the slab and the top of column.
3. Provide a pin to reduce the top of column moments.
4. Augment slab reinforcement and/or incorporate a drop cap.

The subcommittee is currently performing analyses of slab bridges designed using the charts to see when the slab reinforcement cannot meet the capacity-protection requirements for the better columns (shaft/pile extensions).

Precast Bridges

Caltrans began designing precast girder bridges to meet all the SDC requirements in 2000 on the San Mateo Hayward Bridge widening. This 7.5 km (4.7 mile) long bridge supports precast girders on bent caps designed to provide full continuity of all the reinforcement to meet the joint shear requirements for the column plastic moment. Once construction commenced, they were able to build over 30 m. (100 ft.) of bridge every day despite the complicated connections between the girders and the bent cap.

There have been several recent tests of the seismic resistance of precast girder bridges with emphasis on the bent cap (Veletzos, 2006) (Snyder, 2011). These tests included inverted 'T' bent caps supporting different types of precast girders. Caltrans

OEE would prefer to have positive girder reinforcement through the bent since this most closely matches the SDC requirements and ensures that all damage occurs in the column plastic hinge. A design that Caltrans is exploring with Prof. Sritharan at Iowa State University. The girders would sit on the inverted 'T' bent cap and the bottom prestressing tendons would wrap around the four # 11 (#36 metric) rebars.

Another alternative that Caltrans is exploring with UN Reno (Saiidi, 2013) are Next Generation Bridge (NGB) Components for Accelerated Bridge Construction (ABC). This project, which started in 2007, has compared the performance of precast columns attached with couplers to the foundation to the performance of Caltrans standard cast-in-place (CIP) column and foundation. So far, five configurations have been tested: (1) the CIP column, (2) precast column attached to upset headed coupler without pedestal (HCNP), (3) precast column attached to ductile cast-iron grout-filled sleeve without pedestal (GCNP), (4) precast column attached to upset headed coupler with a pedestal (HCPP), (5) precast column attached to ductile cast-iron grout-filled sleeve with a pedestal (GCPP). The precast columns are hollow shells that are filled with self-consolidating concrete after they are attached to the foundations. The pedestal is to move the connection above the plastic hinge zone. So far the tests have been encouraging. The HCNP had better displacement capacity but the GCNP was easier to assemble. The tests will continue. Eventually, Caltrans hoped to test a complete assembly of precast footings, precast columns, precast bent cap, and precast girders. A serious issue for Caltrans is to make sure that these precast elements not only give good seismic performance but are practical to construct and don't become a maintenance problem.

Steel Bridges

Steel Girder Bridges can be quickly constructed with minimum interference to traffic, which make them an important bridge type for Accelerated Bridge Construction. The seismic design of steel bridges is addressed in Caltrans Steel Bridge Seismic Design Criteria (Caltrans, 2001). The seismic design of steel girder bridges is addressed in Caltrans SDC. The challenge is to design the connections for these bridges to be capacity protected.

Long-Span Bridges

Projects like the East Spans of the San Francisco Oakland Bay Bridge have given Caltrans a chance to reflect on issues related to long span structures. The towers need to remain in service after large earthquakes and so shear links between the tower legs were designed to act as a fuse and protect the towers from damage. However, this ERE hasn't been extensively tested and issues such as the welds, anchorage, replacement after earthquakes, etc. need to be studied before shear links become standard equipment for bridge towers.

Caltrans requires a ductility capacity of at least three as a safety factor in case the primary ERE were to fail or if an unexpectedly large earthquake were to occur. Therefore, Caltrans has ductility and post yield performance requirements of hollow columns and towers on long-span bridges. Recent tests of hollow columns have shown promise, but nothing like the ductility of solid columns with closely spaced large diameter hoops. It seems illogical to accept less strength and ductility for the columns of more expensive bridges. Caltrans recommends that hollow rectangular columns have large compression members in the corners connected with very strong diaphragms so the whole section is fully engaged during the earthquake. The compression members should extend beyond the diaphragms so that bending is taken by the compression members rather than the diaphragms. Other requirements include:

1. **Cross ties with 180 degree hooks and 9 diameter heads.**
2. **Columns must have 900mm (3’) minimum wall thickness for tall towers.**
3. **#24 metric (#8 US) inner bars.**
4. **#43 metric (#14 US) outer bars.**
5. **Number of inner bars must be at least 50% the number of outer bars.**
6. **Main reinf. > 1% includes inner and outer bars based on solid section.**
7. **200 mm (8") min. bar spacing, with stirrups at vertical bar.**

CHANGES TO SEISMIC DESIGN FOR OTHER HIGHWAY STRUCTURES

Caltrans is beginning to design other highway structures (besides bridges) for earthquake loads. Caltrans typically addresses ‘life safety’ for the seismic design of bridges and that has also been the focus for the seismic design of retaining walls, tunnels, and other highway structures.

Retaining Walls

For the past few years there has been considerable debate on how to design retaining walls for earthquake loads. Some engineers advocated applying the earthquake force (P_{AE}) at a height of H/2 or at H/3, while others argued that we should be designing retaining walls for a displacement similar to what we do for bridges. Currently, Caltrans uses designs retaining walls using KAE which is function of 1/3 of the Peak Ground Acceleration (PGA) for designing retaining walls but that could be a very large load since Caltrans PGA > 1.0g at many locations. Also, there is concern about having to design every retaining wall for earthquakes. This would require a lot of resources that may not be required when life safety is the main concern. Caltrans has pre-designed cantilever and gravity retaining walls on spread footings and piles in the Standard Plans that have been checked for the reduced seismic acceleration of 0.33(PGA $\leq$ 0.6g). Caltrans concern is for sites in California where PGA $\geq$ 0.6g.

Tunnels

Caltrans has been building a lot of tunnels recently (Doyle Drive, Devil's Slide, Caldecott, etc.) and so tunnel seismic design criteria has been developed. The seismic design philosophy is the same as for bridges. The walls (or liner) are designed to be ductile and the crown and invert are designed to be capacity protected. During large earthquakes the tunnel is able to displace in a controlled manner (as long as P-Δ is small).

NEW EARTHQUAKE RESISTANT ELEMENTS (ERES)

Caltrans would like engineers to be able to choose from a variety of EREs depending on the bridge and the seismic hazard. We have already discussed column plastic hinges, ductile steel end diaphragms (for steel girder bridges), and shear links for bridge towers.

Abutment Embankments

An ERE that is commonly used for Ordinary Standard Bridges is yielding of the soil behind the abutment. The soil has an initial stiffness K_i =28.7 KN/mm per m of backwall (Ki=50kips/in per ft of backwall). The abutment stiffness, K_{abut} is K_i times the area of the backwall, and the effective stiffness, K_{eff} is adjusted for the gap in seat type abutments. The backwall is assumed to yield when the passive pressure reaches 239 kPa (5.0 ksf) times the backwall area. The structure's period is obtained from its mass and stiffness and the Design Spectra is used to obtain the acceleration and/or displacement. R_A equals the computed displacement divided by Δ_{eff} (the displacement when the backwall yields). Then the final stiffness of the abutment (K_{res}) is adjusted depending on the value of R_A.

If $R_A \leq 2$: The abutment controls the displacement $K_{res} = K_{eff}$.

If $R_A \geq 4$: The abutment contribution is small, reduce stiffness $K_{res} = 0.1K_{eff}$.

If $2 < R_A \leq 4$: The abutment stiffness is adjusted between $0.1K_{eff}$ and K_{eff} based on R_A.

Isolators

An ERE that shows promise are isolators such as lead rubber and friction pendulum bearings (AASHTO, 2010). They yield at a smaller force than column plastic hinges so the foundations can be made smaller and they prevent column damage so the bridge can be returned faster to service. A subcommittee was formed to develop design criteria for Ordinary Standard Bridges using isolators and other EREs. The goal is to require similar behavior so that the bridge has the same level of safety no matter which ERE is chosen.

1. **Isolated bridges shall meet the requirements in Caltrans SDC.**
2. **Isolated bridge displacement is determined using AASHTO Isolation Guide.**
3. **Hazard is determined using Appendix B of the SDC (reduced for damping).**
4. **Isolators are designed with a safety factor of 1.25 times displacement demand.**
5. **All the substructure elements must have about the same stiffness and mass.**
6. **All the isolators must have the same stiffness and displacement capacity.**
7. **Bridge columns are designed to remain elastic for lateral isolator forces.**
8. **Bridge columns are designed for $V_u \geq 1.2*F_{1.25\Delta D}$ (1.2 times the lateral force).**
9. **Bridge column lateral capacity > 0.15g (0.15 times dead load reaction)).**
10. **Bridge columns must have a displacement capacity (beyond yield) > 3.0.**

Rules were developed to provide enough strength in the isolators to handle service and wind loads or shear keys should be provided to protect isolators from service and wind loads. Seats or catcher blocks are also required just in case the isolator breaks. No special requirements are made for expansion joints, which are allowed to break (and be quickly repaired) for the Design Earthquake.

Dampers

At one time Caltrans was hoping that viscous dampers would prove to be an effective ERE until they began leaking on several bridge retrofit projects. Because of the cost of having to replace these big dampers, Caltrans Structures Maintenance is reluctant to put them on any more state bridges. Recent retrofit projects (such as the Forest Hills Bridge) have used Buckling Restrained Braces (BRB) with good results. Also, there is hope that liquid-silicone filled dampers can be used instead of oil-filled dampers without all of the maintenance problems. Caltrans has funded research on shape memory alloys that may one day be used as bridge dampers.

Rocking

Caltrans is currently writing procedures that will allow rocking as an acceptable ERE for new bridges. Caltrans has always allowed rocking for bridge retrofits, but the seismic performance requirements for new bridges is higher. Caltrans has funded several research projects on rocking and the results are positive enough to begin discussions on allowing rocking for short bridges where Geotechnical Services recommends spread footings (Kutter, 2010) (Panagiotou, 2014). Similar to isolation bearings, bridge foundations that rock reduce the seismic force, require smaller footings, and should return the bridge to service more quickly.

Self-Centering Columns

Researchers are testing bridges that can remain relatively undamaged and can be put back into service soon after an earthquake. The University of Washington, Stanford University, and the University of California at Berkeley are all doing research into precast columns with a hole in the center for post tensioning cables that automatically re-center a bridge after an earthquake (Cohagen, 2009) (Lee, 2009) (Jeong, 2008). Since these columns would be quicker to assemble, this would meet Caltrans goal of accelerating bridge construction. However, Caltrans still has concerns about the ductility, the constructability, and maintenance of these columns.

Ductile Steel Elements

We have already touched on a few steel earthquake resisting elements. Shear links were constructed on the tower of the new East Bay Bridge in San Francisco Bay. These are similar to the eccentrically braced frames that are sometimes used in steel buildings. The use of ductile end cross frames on steel girder bridges also holds promise (Bahrami, 2010). After the 1999 Duzce, Turkey Earthquake the almost completed Bolu Viaduct suffered major damage to crescent moon-shaped steel dampers placed between a central hub and outer ring. Although the dampers performed well during an earlier earthquake, the Duzce earthquake caused very large displacements that the dampers could not handle.

IMPROVED ANALYSIS METHODS FOR SEISMIC HAZARDS

Caltrans has developed new methods of obtaining the seismic demands on bridges due to ground shaking, surface faulting, lateral spreading, and tsunami hazards. Depending on the bridge site some of these hazards need to be combined in the analysis.

Ground Shaking Hazard

In 2007, Caltrans began taking the envelope of the largest deterministically derived and probabilistically derived ground motion at the bridge site. The probabilistically derived ground motion was the largest ground shaking that had a 5% probability of occurring in 50 years from nearby faults. This hazard level (a 1000 year return period) was agreed upon by the members of the AASHTO T3 Committee after several years of study and it was used in the AASHTO Guide Specifications for LRFD Seismic Bridge Design and in Caltrans Seismic Design Criteria. A third ground motion due to an earthquake on a M6.5 fault that is 12 km from the bridge site is included as the Minimum Deterministic. Caltrans spectra can be obtained for any bridge site in California at (http://dap3.dot.ca.gov/ARS_Online/index.php).

The demands due to the ground shaking hazard are currently obtained using the Equivalent Static Analysis (ESA) Method, the Elastic Dynamic Analysis (EDA) Method, or the Nonlinear Time History Analysis (NTHA) Method. No matter which method is used, the input ground motion comes from response spectra provided on the ARS Online website (and described in Appendix B of Caltrans SDC). Caltrans plans to move to using only probabilistically-derived ground motion by 2016.

At a recent meeting of Caltrans Seismic Advisory Board, Professor Ed Wilson spoke critically of the EDA Method. He said:

- EDA Method is only exact for SDOF systems.
- It produces only positive numbers for displacement and member forces.
- Results are maximum probable values that occur at an unknown time.
- Short and long duration earthquakes are treated the same.
- Demand/Capacity ratios are always overly conservative.
- EDA Method does not provide insight into bridge dynamic behavior.
- Results are not in equilibrium.

Caltrans would like to introduce procedures to perform a nonlinear time history analysis for Standard bridges. The problem is providing sufficient probabilistically-derived time histories of ground motion that are as statistically reliable as a response spectra. There is currently research at the PEER Center on ground motion selection and scaling for nonlinear analysis (Rezeaeian, 2010), which Caltrans will be incorporating into their new analysis procedure. The plan is to create sufficient synthetic time histories for the characteristics of the bridge site, scale the time histories to the probabilistic response spectra at the fundamental bridge period(s), and analyze the bridge using these scaled time histories at increments of 30° to obtain the maximum demands on bridge members.

Similarly, when engineers use the EDA method, Caltrans now requires that the CQC3 method shall be used to obtain the maximum ground shaking demands on bridge members in their local axis (Menum, 1998). Currently, the same ground motion is applied in two orthogonal directions, but the use of CQC3 will provide the correct demands if different response spectra are applied in different directions.

Surface Faulting Hazard

Surface faulting hazards are obtained from Holocene Epoch faults based on the California Geological Survey (CGS) Alquist-Priolo Maps as well as from site investigations and literature reviews. Similar to the ground shaking hazard, the deterministically-derived fault offset is obtained based on fault characteristics using Wells and Coppersmith or other empirical relationships (Wells, 1994). The probabilistically-derived offset is obtained using a report by the San Francisco Public Utility Commission (Abrahamson, 2008).

Once the fault is located and the offset is obtained, the bridge foundations are moved into the offset position and the column displacements are obtained from a 3D model of the bridge. Then the ground shaking displacements are obtained for an elastic version of this bridge in a similarly deformed state (Chopra, 2008).

More information on determining surface fault hazards is provided in Caltrans Memo to Designers (MTD) 20-8 and MTD 20-10 (Caltrans, 2012).

Tsunami Hazard

Tsunami hazards were obtained through a research contract between the Pacific Earthquake Engineering Research (PEER) Center and URS Corporation (Thio, 2010). Seismic sources around the Pacific Ocean were identified and a finite difference model was developed to obtain the wave heights and velocities along the coast of California. Similar to other seismic hazards the 1000-year tsunami wave is being considered for use in design. Information on designing for tsunami is provided in Caltrans MTD 20-13. Recent research by Solomon Yim at Oregon State University (Yim, 2013) will be used to update MTD 20-13 and give designers equations for determining the tsunami wave forces based on the wave height and velocity at their bridge site. Caltrans is also working with other western coastal states on tsunami design guidelines.

Liquefaction and Lateral Spreading Hazard

Caltrans Geotechnical Services is currently developing standard methods for evaluating seismic hazards in the ‘Geotechnical Manual,’ which will be completed in 2014. http://www.dot.ca.gov/hq/esc/geotech/geo_manual/manual.html.

A new procedure has been written for determining demands on bridges due to lateral spreading, based on research funded by Caltrans (Shantz, 2012) (Ashford, 2010). Caltrans MTD 20-14 and MTD 20-15 provides designers with simple procedures for designing bridges for liquefaction and lateral spreading, but these memos may need to be revised based on new information and procedures.

Conclusion

After the 1989 Loma Prieta Earthquake Caltrans greatly increased its funding for seismic research, mostly directed at retrofitting Caltrans existing bridges. As the retrofit program neared completion, Caltrans changed its focus from research on existing bridges to the seismic design of new bridges. In 1999 Caltrans Seismic Design Criteria was first published, based on lessons learned from earthquakes and from Caltrans research program. Despite not having any damaging earthquakes in a number of years, Caltrans still supports a great deal of earthquake-related research.

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