The California Department of Transportation (Caltrans) Office of Earthquake Engineering

Mark Yashinsky

Senior Bridge Engineer, Caltrans Office of Earthquake Engineering MS9
1801 30th Street, Sacramento, CA, 95816 USA
Email: Mark.Yashinsky@dot.ca.gov

ABSTRACT:

Caltrans Office of Earthquake Engineering (OEE) is responsible for developing bridge seismic design and retrofit criteria in California. We also develop seismic criteria for tunnels, retaining walls, and other highway structures. The Office manages $4.2 million in earthquake-related research every year. We advise Caltrans engineers, consultants, and other agencies on the state-of-the practice for earthquake engineering for bridges. Advanced seismic analysis of bridge structures is performed by our office. We work closely with Caltrans Office of Geotechnical Services to ensure that there is agreement on analysis and design methods for foundations, on developing site specific ground motions, on retaining wall design, and on other areas where geotechnical and structural engineers need to coordinate.

KEYWORDS: Caltrans, Bridges, Highways, Earthquakes, Engineering

1. INTRODUCTION

The Office of Earthquake Engineering was created following the 1989 Loma Prieta Earthquake to ensure that Caltrans could make use of the latest knowledge about earthquakes and their effect on highway structures. The Office's first task was a bridge retrofit program. A database of state bridges was prioritized using an algorithm (Eqn 1.1) that assigned values based on the seismic **activity** and **hazards** at the bridge site, the **vulnerability** of the bridge, and the **impact** the bridge's collapse or closure would have on society.

$$\text{Priority} = (\text{Activity})(\text{Hazard})[0.6(\text{Impact}) + 0.4(\text{Vulnerability})] \qquad \text{Eqn 1.1}$$

Much of the Office's efforts during the retrofit program was to take the latest research and turn it into design and retrofit criteria that could immediately be used by engineers. Every bridge retrofit had a strategy meeting attended by OEE staff to ensure the retrofit was effective in preventing a bridge collapse without wasting the public's money. This retrofit program protected bridges with brittle columns by using steel or composite casings, it protected bridges with short seats by using hinge restrainers as well as pipe seat extenders, and it protected bridges with weak foundations by using pile cap extensions. The retrofit program was completed in 2004 with over 2000 bridges retrofitted at a cost of about $5 billion.

As the retrofit program neared completion, the OEE, with considerable assistance from the Office of Structure Design (OSD), took the knowledge it had gained and used it to develop seismic criteria for the design of new bridges. Caltrans' Seismic Design Criteria (SDC) was first published in 1999 and updated every couple of years as new research and other information became available. Also a new seismic hazard map for designing and retrofitting California's bridges was created and published by OEE in 1996, making use of the latest research on late Quaternary faults and the latest attenuation relationships for strike-slip, normal, and reverse faulting based on recorded ground motion.

Since much of our knowledge is based on data collected from earthquakes, the OEE manages its own earthquake investigation team. The OEE has earthquake pagers that notify engineers when an earthquake causes shaking at any one of the thousands of strong motion accelerometers scattered across the state. Automated ShakeCast software sends emails to OEE staff that includes contour maps of ground motion and the location of potentially impacted bridges. The OEE investigation team goes out to make a record of the performance of highway structures and to write a report that is reviewed by Caltrans management to determine if changes are needed to Caltrans Seismic Criteria. The OEE has published reports following the 1989 Loma Prieta, the 1994 Northridge, and the 1999 Hector Mine Earthquakes. With the coming of the Internet, more recent events such as the 2003 San Simeon and 2007 Alum Rock have been reported on the OEE website at: **http://www.dot.ca.gov/hq/esc/earthquake_engineering/.** A great deal of other information: past and present research projects, the post-earthquake investigation manual, the current seismic hazard map, upcoming seismic conferences, etc. can be found on this website.

2. CURRENT ORGANIZATION AND RESPONSIBILITIES WITHIN THE OEE

The California Department of Transportation (Caltrans) is divided into 12 Districts with the Division of Engineering Services (DES) providing engineering support to the districts. The Structure Design Services and Earthquake Engineering (SDSEE) Subdivision is one of nine subdivisions within the DES. The Office of Earthquake Engineering (OEE) is one of ten offices within the SDSEE. The OEE is divided into four branches with a total staff of about 35 licensed engineers (Figure 2.1).

2.1 Responsibilities of the OEE Office Chief

The OEE Office Chief (currently Mike Keever) manages the four OEE branches and reports to the Deputy Division Chief for SDSEE. However, the OEE Office Chief's responsibilities extend well beyond the SDSEE. Some projects like the new seismic hazard map are being developed by the Geotechnical Services Subdivision but require supervision from the OEE. Other projects like seismic hazards research, are managed by Caltrans Division of Research and Innovation (DRI), but also require supervision from the OEE. Our office works with the California Geological Survey to instrument bridges and down-hole arrays with strong motion accelerometers. We are working with Transportation Planning to develop lifeline routes that remain in service following earthquakes. We are working with Structure Maintenance to improve the database for state bridges to include properties that describe the bridge's expected seismic performance. We have often felt that if all

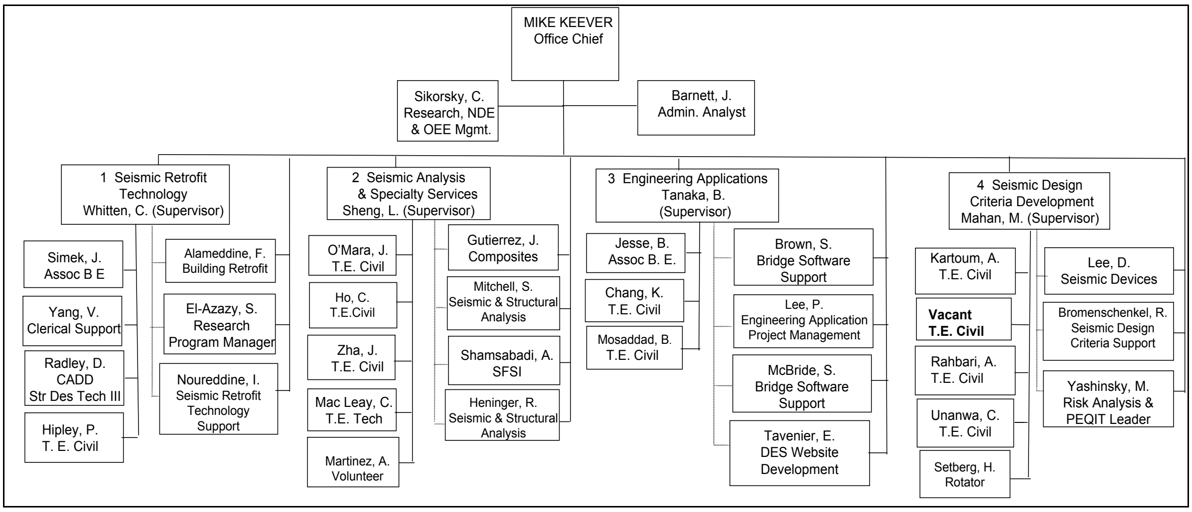

Figure 2.1 Organization Chart for the Office of Earthquake Engineering

seismic work were handled within the OEE, it would make our life easier. However, earthquake engineering touches on so many disciplines, it probably could never be contained within one Office.

The OEE Office Chief and DES Deputy Directors meet periodically with a Seismic Advisory Board (SAB) from outside of Caltrans. An Executive Earthquake Committee (EEC) made up of DES managers meet to discuss seismic policy on a monthly basis. Not only do the four OEE branch chiefs meet with Keever every week, but engineers working on special projects also need to meet with him.

2.2 Seismic Retrofit Technology Branch

The Seismic Retrofit Technology (SRT) Branch updates Caltrans retrofit guidelines (contained in Memos to Designers 20-4), develops strategies and devices to protect existing bridges from earthquakes, identifies vulnerabilities that still need to be addressed, develops better screening methods to identify potential vulnerabilities, works on funding mechanisms for new retrofit programs, and consults with engineers on their retrofit projects.

Bridge prioritization algorithms continue to be based on seismic activity and hazards, the vulnerability of the bridge and the impact of its collapse or closure. As we learn lessons from earthquakes, these variables have become more complex. Unfortunately, our database of bridge attributes can hardly do justice to the need for increasing sophistication. Caltrans' bridge database is managed by the Division of Structures Maintenance and Investigations (SMI), but they have their hands full recording the bridge's health without the additional burden of documenting its seismic vulnerabilities. Improving the bridge database to include soil data, column data, expansion joint data, etc. has been a priority of our Office since it was formed, but we are no closer to a solution. What makes this problem even more difficult is time. Every year hundreds of new bridges are built and hundreds of old bridges are torn down. Every year, our seismic design criterion is modified. Every year, the data we need to evaluate seismic risk (activity, hazards, vulnerability, and impact) changes due to a better understanding of earthquakes and a changing inventory of bridges.

An intermediate step between a screening and a full analysis is the use of bridge fragility curves. Bridges are assigned fragilities based on the likelihood of damage or collapse for increasing levels of shaking (or other seismic hazards). Each bridge is assigned its geographical location and subjected to one or more earthquakes. The result is a prioritized list of bridges ranging from the most to least damaged for different scenario events. This type of simple analysis is used to direct engineers to the most damaged bridges following an earthquake and to alert government officials on the state of highways for large events. Unfortunately, the current fragility curves (based on the bridge database) are overly conservative and represent a key area of future research.

In the meantime, we are continuing our screening process, looking at bridges that may cross faults, reviewing some of our early retrofits, and looking at bridges that mix short and tall columns in the same frame. Last year we completed a screening of a few remaining bridges with short seats. Our new retrofit policy emphasizes the use of pipe seat extenders for short hinge seats. We are actively involved in the seismic retrofit of the Antioch and Dumbarton toll bridges, with the retrofit strategies currently pointing toward extensive use of seismic isolators.

Another perplexing issue for the SRT is enhanced performance criteria, particularly for bridges on so-called 'lifeline' routes. Almost all of California's bridges have been designed and/or retrofitted to prevent collapse during the maximum earthquake. Identifying bridges requiring higher performance criteria has been a difficult process. Activist communities insist all of their streets and roads are 'lifelines' while less vocal communities have no lifeline routes. Some routes have been identified by a committee as needing 'hardening' for national security or economic reasons, but it is our Office's belief that these routes should be re-examined using a more rigorous method of analysis. What is required to keep lifeline routes open following an earthquake? Is identifying detours around vulnerable structures sufficient to allow emergency traffic through after an earthquake? Providing enhanced performance is simple to achieve for new bridges but it's difficult for existing structures.

Memo to Designers 9-3 requires that when widening a bridge, the existing structure must be evaluated and upgraded if necessary to meet current seismic retrofit standards and performance goals. Similar evaluations may be required when other bridge modifications are being designed. This has the impact of making routes with higher traffic demands end up with higher seismic performance than less-traveled routes. This may be a good thing, but currently no one is tracking which bridges and routes have been retrofitted in this manner, another example where the SRT could benefit from a dedicated staff for data acquisition.

2.3 Seismic Analysis and Specialty Services Branch

The Seismic Analysis and Specialty Services (SASS) Branch is in charge of performing advanced seismic analyses and advancing the use of composites, damping devices, soil-structure interaction, and other techniques to reduce bridge damage from earthquakes.

Over the past decade SASS has helped Engineering Services move to the use of SAP2000 as the primary analysis tool for seismic demand and capacity analyses, push-over analyses, time history analyses, nonlinear analyses, eigenvalue analyses, as well as analyses for extreme loads and unusual structures. The SASS has worked with Computer & Structures, Inc. (CSI) to make SAP2000 a much more user-friendly tool for bridge engineers. This has resulted in Bridge Modeler, Section Designer, and a variety of nonlinear elements such as fiber hinges, expansion joints, nonlinear soil springs, etc.

Other analysis tools in SASS's arsenal are ADINA, which was used for modeling the existing San Francisco Oakland Bay Bridge. SASS has a contract with SC Solutions to provide a model of Caltrans' toll bridges. After an earthquake, these bridges can be analyzed using nearby free field ground motions, and locations of bridge damage can be identified. The bridge model can be modified to better match the accelerations recorded on the bridge during the earthquake.

The SASS provides support to bridge engineers and it offers courses in performing seismic analyses, but its main function is to perform difficult structural analyses. Often, when there is an immediate concern for a bridge's safety, SASS will be asked to quickly model the structure, check the loads, and recommend a solution. Recent projects include:

- Tendon pull-out analysis for the post-tensioning failure of a bridge in LA.
- Scaffolding analysis for the West Bay Bridge retrofit construction failure.
- Coronado Bridge paint scaffolding analysis.
- Carquinez Bridge demolition analysis.
- Bryte Bend Bridge jacking analysis including detailed buckling analysis.

Currently, the SASS is busy analyzing the Dumbarton and Antioch Toll Bridges to see if they need a retrofit to prevent severe damage following the maximum earthquake. Global models of each bridge were created (with 6 x 6 matrices to capture the foundation stiffness) and analyzed with response spectra to obtain the demands. Then, each pier was modeled with fully nonlinear P-Y, T-Z, and Q-Z soil springs, plastic hinges, and pushed over to duplicate the pier displacement in the global model. Currently, the piles seem to be the most vulnerable elements and the SASS is considering isolation bearings to reduce the load going into the substructure. Unfortunately, there is not a lot of room to fit an isolation device under the existing 'delta' shaped precast girders (see Figure 2.2 below).

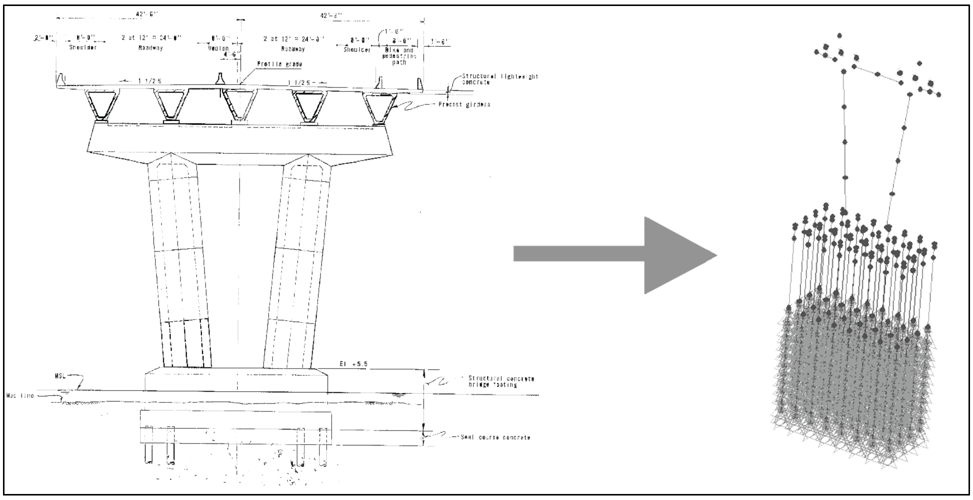

Fig 2.2 Push-Over Model of Dumbarton Bridge Pier.

2.4 Engineering Applications Branch

The Engineering Applications Branch creates, maintains, and updates structural analysis software used by Caltrans bridge engineers. Surprisingly, not all of the software is directly related to earthquakes. OEE has become a convenient environment for the development and maintenance of all bridge design and analysis software. Bridge engineers may not write the most elegant software codes, but they are able to produce products that are quickly adopted and have proven very useful to other bridge engineers. After the Loma Prieta earthquake, Caltrans engineers had few tools to perform a moment-curvature analysis or a push-over analysis. Mark Mahan, an engineer in Caltrans Office of Earthquake Engineering, not only was able to write the software, but he was able to convince other bridge engineers to use it. In fact, Mark sat in the Office of Structure Design for several years to provide support to bridge engineers.

Today, the Engineering Applications Branch within the OEE is tasked with meeting most of the software needs for the OEE and Engineering Services. Some of this software is a legacy from the old days when engineers did their analyses on mainframe computers. Even today, some of the software still runs in DOS, where it does an excellent job, despite the lack of a GUI interface. However, most of the software written in the last 10 years was written in Visual Basic, C+, or Java, and, runs in the Windows environment on menus with pre and post processing of the analysis.

There is software for designing foundations (WinFoot and WinNFoot), for designing substructures (WinYield, WinAbut, and CTBent) and for designing superstructures (CTBDS and CTBridge). There are programs for performing a moment-curvature analysis (XSECTION and PSSEC), for performing push-over analyses (WFRAME), and for performing a rocking analysis (WinRock). There is general purpose software for reinforced concrete and prestressed concrete design (WinConc and PSBeam). There is software for designing culverts (CTBC), for designing retaining walls (CTFlex), for plotting deck contours, for determining bridge alignments, etc.

Bridge design and analysis software not only has changed with the adoption of new computer operating systems but also with the advancement of new bridge design codes. Perhaps the biggest recent change to our design software was when all 50 states adopted the American Association of State Highway and Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Specifications a few years ago. This followed a trend in the engineering community to move to a statistics-based method to ensure a similar probability of failure for all elements. Bridges designed with the LRFD specifications have more uniform safety levels to ensure serviceability and reliability. The move from LFD to LRFD made a big change in most bridge design software. The biggest change was to the software used to design the superstructure of most bridges. With the adoption of LRFD, Caltrans switched from CTBDS to CTBridge.

Today, much of the older, DOS-based software is available free to the public while some of the newer, more sophisticated software is sold to the public. In fact, CTBridge, which incorporates the latest AASHTO specifications, costs $2500 for a full, single user license (http://caltrans-opac.ca.gov/publicat.htm).

Another service provided by the Engineering Applications Branch is the creation of dozens of websites and web-links for the OEE. Today, most information, products, and services provided by the OEE can be conveniently obtained from the Internet.

2.5 Seismic Design Criteria Development Branch

The Seismic Design Criteria Development (SDCD) Branch, as its name implies, is in charge of developing seismic criteria for use by bridge engineers in California. Caltrans has written its own seismic specifications since the 1971 San Fernando Earthquake, which demonstrated how vulnerable bridges are to earthquakes. A week after the earthquake, Caltrans began requiring bridge columns to have closely-spaced spiral reinforcement, longitudinal column reinforcement to be developed into foundations and bent caps, and foundations to have a top and bottom mat of steel and stirrups. Even bridges that had been designed but not constructed before the earthquake were required to have change orders to meet the new specifications. Caltrans also took the lead in specifying the seismic hazard, developing criteria that took into consideration the attenuation of the ground motion with distance from the fault and amplification of the ground motion (for certain periods) based on the soil at the bridge site.

Caltrans has continued to take the lead for bridge seismic design in the United States. It wasn't until after the 1989 Loma Prieta earthquake that the Federal Highway Administration (FHWA) required all states to use ATC-6 (Sharpe, 1981), which was based on Caltrans 1971 seismic criteria. The new AASHTO Seismic Guide Specifications (Imbsen, 2006) is very similar to Caltrans current Seismic Design Criteria (SDC), at least for regions of the United States with high seismicity. In fact, Caltrans was so pleased with the new AASHTO Guide Specs, that we are considering adopting it (while continuing to update some sections to meet our own needs).

The SDCD continues to work on a variety of documents, including a new version of Caltrans' Seismic Design Criteria (the fifth update), scheduled to be published later this year (to coincide with a new seismic hazard map). Among the changes in the new SDC are:

- A better method of designing column connections for joint shear.
- Design criteria for foundations built in liquefiable soil.
- A new policy for cable restrainers.
- Requirements to designing bridges for deterministic and/or probabilistic ground motions.

Some of these changes are the result of lessons learned following earthquakes. In fact, engineers from the SDCD try to study bridge performance after every earthquake, whether it occurs in California or in China to see what lessons can be learned. The SDCD has developed criteria for a variety of seismic hazards such as near-fault effects, surface faulting, and even tsunami based on lessons learned from recent earthquakes all around the world.

Similarly, the SDCD nurtures OEE-sponsored research in the hope that it will prove as valuable as lessons learned from earthquakes. Input between bridge engineers and researchers results in more practical research. Therefore, SDCD assigns a research monitor (usually someone with a lot of design experience) to every project. The SDCD manages the General Earthquake Committee (GEQC), made up of senior bridge engineers, which meets once a month to voice their opinions about the latest seismic research. These meetings can be quite boisterous and its not unusual for arguments to take place. The SDCD Branch Chief also manages the Executive Earthquake Committee, made up of Earthquake Engineering, Structure Design, and Geotechnical Services managers, who must approve all changes to the SDC and other seismic documents.

Research can be conducted by universities, but it is often first performed by a committee formed by the SDCD. For instance, a design engineer asked the SDCD Branch Chief if the current method for modeling pile foundations (just considering the axial load in the piles) was okay. We formed a small committee made up of bridge designers, a geotechnical engineer, and several engineers from the SDCD. A series of analyses were performed and it was found that the pile cap displacement was so small in competent soil, that the pile shear and moment could safely be ignored. Similar committees were formed to study the lateral capacity of standard Caltrans' piles, the effect of shaking on skewed bridges, selecting appropriate ground motions for nonlinear analysis, etc. Sometimes we were able to find a solution on our own, but often the GEQC recommended that the research be continued by someone with more experience such as at a university.

3 RESEARCH

There are several seismic research programs managed by the OEE. The DRI spends about $500,000 a year on seismic hazards research through the Pacific Earthquake Engineering Research (PEER) Lifeline Program at the University of California in Berkeley. The Pacific Gas and Electric Company and the California Energy Commission also support the Center so we are able to get a lot of good research for relatively little money. The biggest recent project has been the Next Generation of Attenuation (NGA) relationships that were recently published (Power, 2008). These attenuation relationships make use of a library of over 2000 earthquake records to provide ground motion based on magnitude, distance from the fault rupture, faulting mechanism, etc. Other projects include a tsunami hazard map that will be used to design bridges along the coast, (Somerville) an effort to correlate PSHA software (Wang), guidelines for the nonlinear analysis of bridges (Stojadinovic), and liquefaction screening at bridge sites (Knudsen). Since 1996 over 110 research projects have been funded by the PEER Lifeline Program (http://peer.berkeley.edu/research/lifelines.html).

The OEE spends about $1 million a year through the California Geological Survey (CGS) on a bridge instrumentation program. About 80 different types of bridges have been instrumented where earthquakes are likely to occur in California. As part of the program, several down-hole arrays have been constructed at bridge sites. Our hope is that when a large earthquake occurs, we will be able to study how the waves move up through the ground surface and excite bridge structures. We also hope to improve the correlation of bridge damage to instrumental recordings during earthquakes.

Whenever an earthquake occurs, the CGS provides money for researchers to perform an analysis on an instrumented bridge and write a report that compares the recordings to the results of their analysis of the bridge excited by nearby free-field ground motions.

The OEE spends about $3 million a year on structural and geotechnical earthquake engineering research. Although these research projects can be proposed by anyone, the OEE identifies most of its own research needs, which are written into proposals, and considered by the Structures Technical Advisory Panel for Research, whose members include the OEE chief. Someone from OEE is assigned to manage each of these projects to ensure the project stays focused on Caltrans' needs and to act as an advocate of the research.

The OEE keeps a database of past and present research projects and a library of research project reports. Many of these reports are available for download from the OEE Website (http://www.dot.ca.gov/hq/esc/earthquake_engineering/). The Office organizes a conference to present the results of OEE funded research to the public. In this way, the latest research can be studied outside of Caltrans and the results subjected to scrutiny and perhaps synergy. When the OEE was first established, only lateral ground shaking hazards were considered in design. Today surface faulting, liquefaction, lateral flow, vertical accelerations, directivity effects, and even tsunami are being addressed by the OEE. This requires research to better understand these hazards, new seismic criteria to protect new bridges from these hazards, and possibly new retrofit programs to protect existing bridges.

4 BRIDGE PROJECTS

OEE is typically assigned to unique or important projects. We have not been as involved in toll bridge projects. Unique or important bridges often get their own seismic criteria, including site-specific ground motions and performance criteria for unusual bridge elements. An engineer from the OEE is assigned to each of these projects to ensure the project adequately addresses seismic issues, and they report to the OEE Chief. Engineers working on ordinary bridge projects often come into the OEE to seeking advice and someone from OEE will attend their bridge type selection meeting. Every new and retrofitted bridge in California must be reviewed by OEE staff including the Bay Area Rapid Transit (BART) bridges, Department of Water Resources (DWR) bridges, city and county bridges, etc. Even the Golden Gate Bridge, which is owned by the Golden Gate Highway and Transportation District, must have its seismic retrofit plans approved by the OEE.

5 PRODUCTS

The OEE provides a variety of products. Classes are given in SAP2000 training including using the software to perform a 'Push-Over Analysis' to obtain the capacities of bridge elements, frames, and structures. Every year the OEE teaches a class on the latest developments at the OEE. Training is provided for engineers on the Post-Earthquake Investigation Team (PEQIT) roster about different aspects of earthquakes, bridge performance, and safety concerns when in the field. The OEE provides training to children during Caltrans annual 'Take Your Kid to Work Day (TYKTWD). OEE staff write papers and speak at conferences about the work being done in the Office.

Beside the SDC, chapters in Caltrans Bridge Design Practice, Bridge Design Details, Bridge Design Aids, and Memos to Designers are written by OEE staff. Chapter 20 of Memos to Designers (MTD) has become a convenient location for the OEE to write seismic policies on specific issues. MTD20-1 discusses seismic performance criteria for different types of bridges. MTD20-2 discusses seismic requirements for construction falsework. MTD20-3 discusses restrainers at hinges and bearings but needs to be updated with recently completed work. Memos to Designers can be obtained at (http://www.dot.ca.gov/hq/esc/techpubs/manual/bridgemanuals/bridge-memo-to-designer/bmd.html).

6 FUTURE DIRECTIONS

The OEE is early in the process of adopting Accelerated Bridge Construction (ABC) techniques in

California, which will need to be carefully designed for earthquakes. The OEE will work with UC-Berkeley to consider the next generation of California bridges, which will likely include elements of ABC along with improved post-earthquake serviceability. Our Office is beginning to become a little more multi-hazard oriented. We went to the Gulf of Mexico to study bridge damage after Hurricane Katrina. We responded to recent emergencies at the MacArthur Maze and 14/5 Tunnel, both caused by fire. We are constructing and planning more tunnels in California and developing tunnel seismic design criteria. We are also in the process of developing seismic design criteria for retaining walls.

We recently updated our seismic retrofit guidance material (MTD20-4), which should be published soon. Later this summer we expect recommendations on the design of bridges susceptible to liquefaction and lateral spreading hazards. We are continuing our screening process, looking at bridges that potentially cross faults, reviewing some of our early retrofits, and looking at bridges that mix short and tall columns in the same frame. Last year we completed our screening of bridges with short seats. Our new retrofit policy emphasizes the use of pipe seat extenders for short hinge seats.

We are actively involved in the seismic retrofit of Antioch and Dumbarton, with the retrofit strategies currently pointing toward extensive use of seismic isolators.

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