INCORPORATING THE USE OF STRONG MOTION DATA INTO PRACTICE IN CALIFORNIA

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ABSTRACT

The California Department of Transportation (Caltrans), through an Interagency Agreement with the California Geological Survey (CGS), has placed strong motion instrumentation on nearly seventy bridges across the state as a component of the California Strong Motion Instrumentation Program (CSMIP). Coupled with the availability of data from a statewide network of over 3000 seismic instruments deployed through the California Integrated Seismic Network (CISN)[1], information collected from instrumented bridges following a strong seismic event will allow the Department to develop a better understanding of bridge seismic response. Ultimately this should lead to improved seismic analysis, design, and detailing methods for bridge engineers. However, recognizing the potential value of strong motion data, this original concept is being expanded in several directions including integration with emergency response, traffic management, damage assessment, and health monitoring activities.

BACKGROUND

At the time of the 1989 Loma Prieta Earthquake, only four bridges were instrumented for strong motion in California. The limitations this imposed on engineers, seismologists and bridge engineering professionals seeking to learn from this experience to improve bridge seismic performance was identified in the post-earthquake investigation by the Governor's Board of Inquiry, who stated "The lack of ground and structural response recordings limits engineering analysis of structural performance and therefore the ability to draw conclusions about the performance"[2] of bridges damaged in the Loma Prieta Earthquake. Following the Board's recommendations, Caltrans thus began an ambitious effort to expand its inventory of instrumented bridges. Currently seismic monitoring devices and free field instrumentation have been installed at 68 bridges across the state, as well as 14 downhole arrays, at a cost of approximately $7 million, with $1.5 million earmarked for expansion of the network over the next three years.

As shown in the Caltrans/CSMIP Strong Motion Instrumentation map (Fig.1), bridges have been selected for instrumentation from throughout the state. These are typically located relatively close to faults identified on the Caltrans Seismic Hazard Map (cite reference here) and in heavily populated metropolitan regions. The intent is to select different bridge types, ranging from typical highway bridges in Caltrans inventory (e.g. prestressed concrete box girder overcrossings), to those with unusual conditions (e.g. outrigger bents, liquefiable soils, wide-ranging soil or structural properties, etc.). There are a number of logistical concerns that are considered in the selection process as well, including the availability of power and telecommunications, the ability to install the instrumentation safely within Caltrans right-of-way, and exposure to vandalism.

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[1] The California Integrated Seismic Network (CISN) operates a statewide system for earthquake monitoring, research, archiving, and distribution of information for the benefit of public safety, emergency response, and loss mitigation. The CISN organization is comprised of the California Geological Survey, Caltech Seismological Laboratory, Berkeley Seismological Laboratory, USGS Menlo Park, USGS Pasadena, and the California Governor's Office of Emergency Services.

[2] Competing Against Time, June 1990

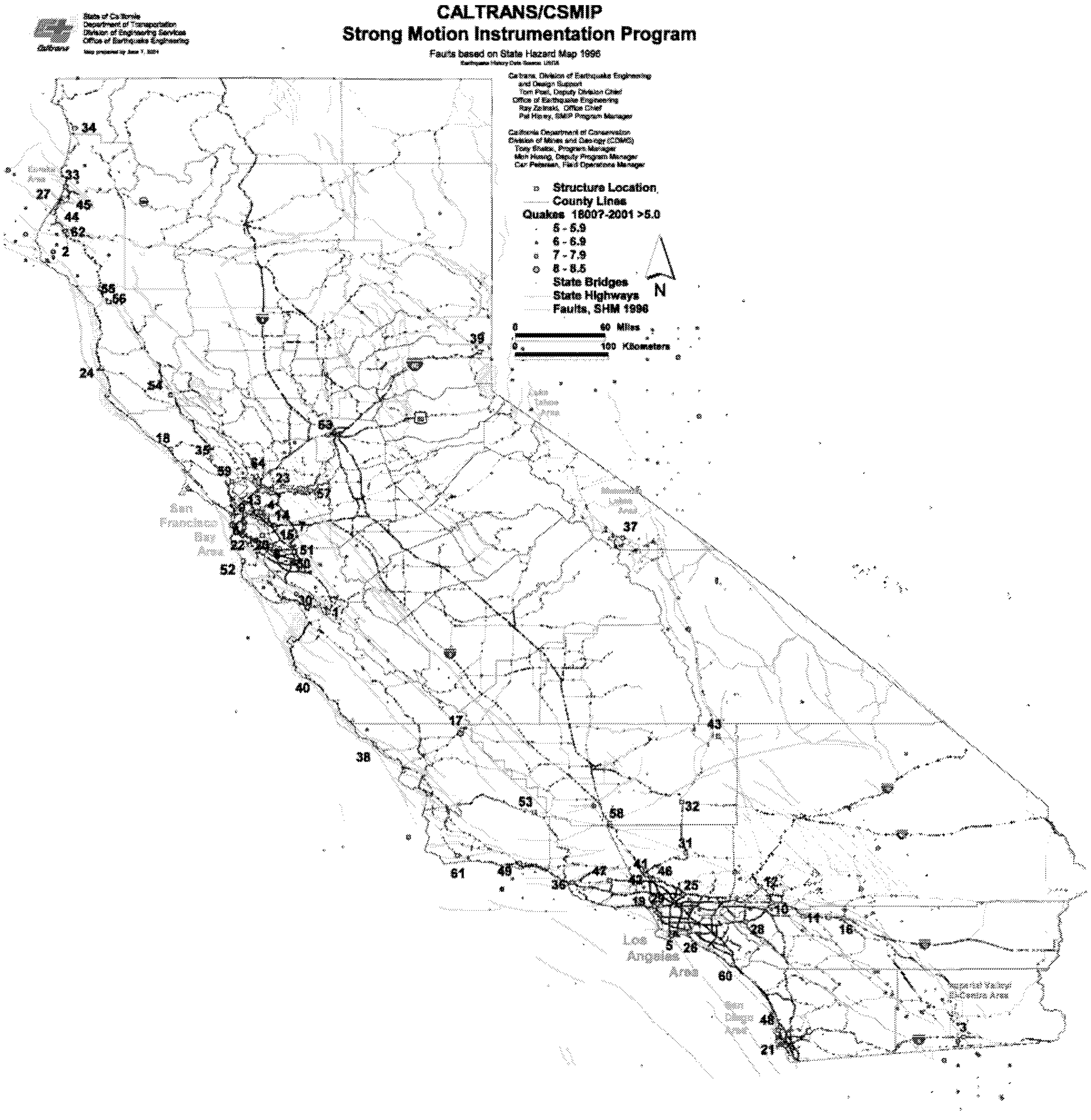


Figure 1 CALTRANS/CSMIP Strong Motion Instrumentation Map

Each bridge is individually evaluated and an array of strong motion sensors are placed as deemed necessary to determine the fundamental displacements and primary mode shapes. Typically this includes placing instruments at bents and midspan locations on the deck, and may include bottom of column or pile cap sensors, and even deep foundation sensors, if significant foundation movement is expected. An example of a sensor deployment is shown in Fig.2 for the Carquinez Bridge on Interstate 80.

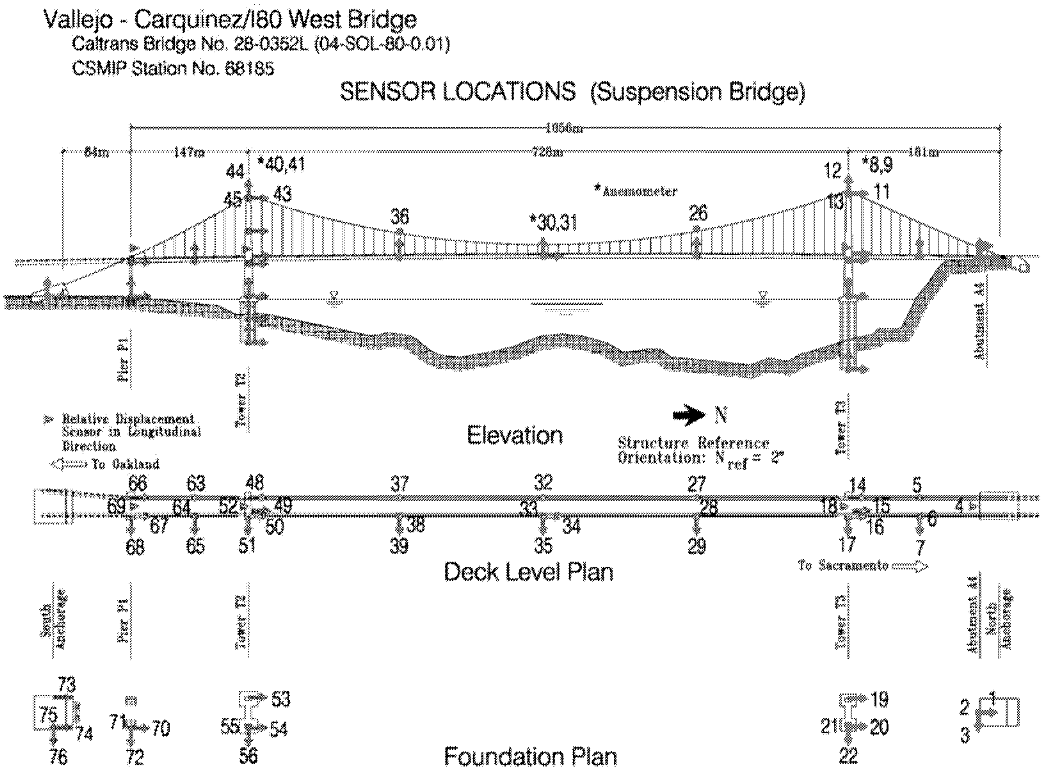


Figure 2 Carquinez Bridge Strong Motion Sensor Plan

At each bridge site, freefield ground motion sensors are placed at a position on the ground near the bridge, but away from structural influences. Deep downhole sensors, some placed as deep as 800 feet below ground (Fig. 3), have been placed at fourteen bridge sites around the state. These sensors are used to collect surface and subsurface soil movement and acceleration data at depth, and coupled with the foundation and structure sensors, verify or update our current understanding of soil-foundation-structure interaction and modeling techniques.

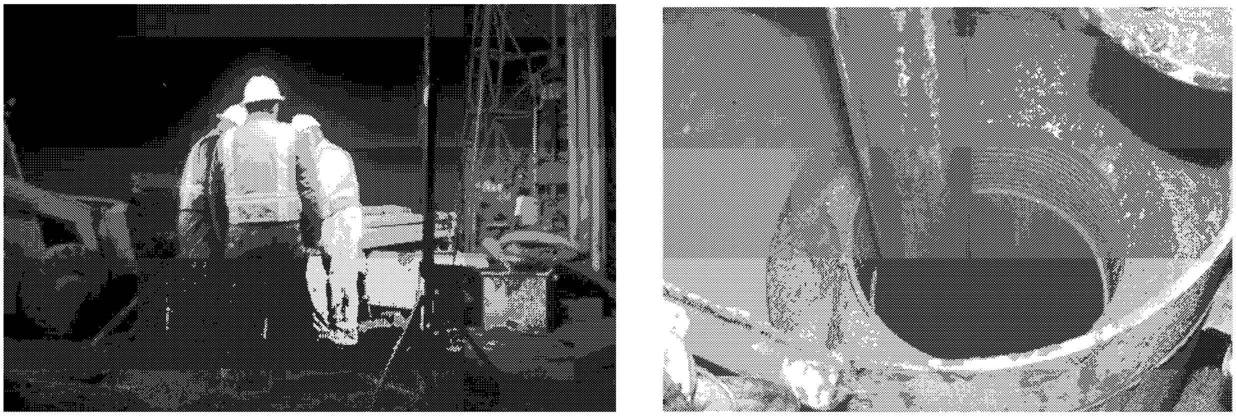


Figure 3 Placement of Downhole Seismic Sensors

ANALYSIS OF BRIDGES USING STRONG MOTION DATA

While the expanded network of CSMIP bridges has yet to capture significant nonlinear response of an instrumented bridge following a large earthquake, several bridge seismic response studies have been conducted using data collected under more moderate events. Several examples are cited below:

- An evaluation was made of the interaction of bridge joints on the Northwest Connector following the June 1992 Landers and Big Bear earthquakes by the California Department of Mines and Geology. This 2540 foot multi-span curved concrete box girder bridge is located at the I10/215 Interchange in Southern California. The 34 strong motion sensors on the 2540 foot multi-span curved concrete box girder bridge captured sharp spikes up to 1.0g from sensors mounted on the bridge deck, while the peak ground acceleration at the bridge site was only about 0.1g. Post-event analysis indicated these spikes were caused by intermittent impact of the hinges and tension when the cable restrainers engaged. This study verified the use of relatively simple formulas to estimate the amplitude, duration and propagation of these acceleration pulses.
- Another study of the same structure was made by the University of California, Berkeley. Their report reviewed the non-uniform response of the multiple bridge supports, the bridge's vibration properties, the influence of banging of the in-span hinges on the seismic response, and an overall assessment of typical bride modeling and dynamic analysis techniques. This study noted changes in the fundamental period and damping of the structure in the two earthquakes, likely the result of softening under the earlier Landers earthquake. This report noted that while standard simple linear analysis modeling techniques was adequate in general, it did not completely envelope the affects of hinge pounding on all of the columns.
- A study of the 1582 foot North Connector Bridge at the Interstate 5/Highway 14 Interchange following the October 1999 Hector Mine earthquake was conducted by Dowell-Holombo Engineering. This 1582' long multi-span concrete box girder bridge was instrumented with 42 sensors. The report compared measurements taken from the seismic instrumentation with results from analysis models of varying levels of complexity utilizing recorded ground motions as input. Damping, concrete strength, and other typical modeling parameters were verified through the study. However, one of the findings was the need to include the rotational mass of the superstructure and bent caps to accurately capture bridge response when using relatively simple spine models,

particularly for single-column-bent structures. This recommendation is currently under study by Caltrans.

- A study of the Route 10/215 Interchange single column viaduct structure in Colton was conducted by Imbsen and Associates using data from the 1992 Landers and Big Bear Earthquakes and from the 1994 Northridge Earthquake. Column behavior characteristics, based on measured deformations which reached up to 70% of the yield deformation, were compared to the deformation-based design methodology results from the seismic retrofit design. A study of the effects of foundation contribution to the column deformation was also made as part of the study.
- A study was made of the Painter Street Bridge in Rio Dell, California following the 1992 Petrolia Earthquake by UC-Berkeley. This study focused on soil-pile foundation-superstructure interaction and the frequency dependence of pile-foundation impedances to the response of the superstructure.

While sensors on bridges instrumented through the CSMIP program have not yet captured high levels of seismic acceleration resulting in nonlinear bridge response, data that has been collected is already yielding valuable information, positively affecting the practice of bridge engineering. It is just a matter of time before seismic monitors capture the dynamic response of an instrumented bridge following a large earthquake. With the investment in the CSMIP program, engineers, seismologists and academicians will be able use the data that is collected from Caltrans-instrumented bridges to gain insight into contemporary earthquake engineering problems such as near field velocity pulse and directivity effects, foundation rocking, soil structure interaction, vertical acceleration, liquefaction, improved structural modeling and other related issues.

EMERGENCY RESPONSE

Following a large earthquake, typically defined as magnitude 6.0 or larger, teams of trained personnel from Caltrans Structures Maintenance & Investigation (SMI), complemented by bridge engineers from Structure Design (SD) are assigned bridges along defined routes for post-earthquake inspection. Procedures used in the past for establishing inspection priorities reflected the lack of precise information about the distribution of damaging levels of shaking. In the absence of such information, the practice had been to use the epicenter location and fan out radially along assigned routes (Fig.4). Another approach was to find the closest fault and develop a list of bridges within a specified buffer zone surrounding that fault.

The problem with epicenter-based or whole-fault based buffer zones is that earthquake shaking levels can vary dramatically within the buffer zone. An earthquake rarely ruptures over the entire mapped fault length. Furthermore, ground shaking at the same distance from a rupture zone can vary by nearly a factor of 10 due to a variety of seismological and geotechnical effects including fault rupture directivity, deep basin effects, and local site response. Buffer zones large enough to account for all areas that could be strongly shaken will include wide swaths of undamaged zones, potentially diverting inspection resources away from critical needs.

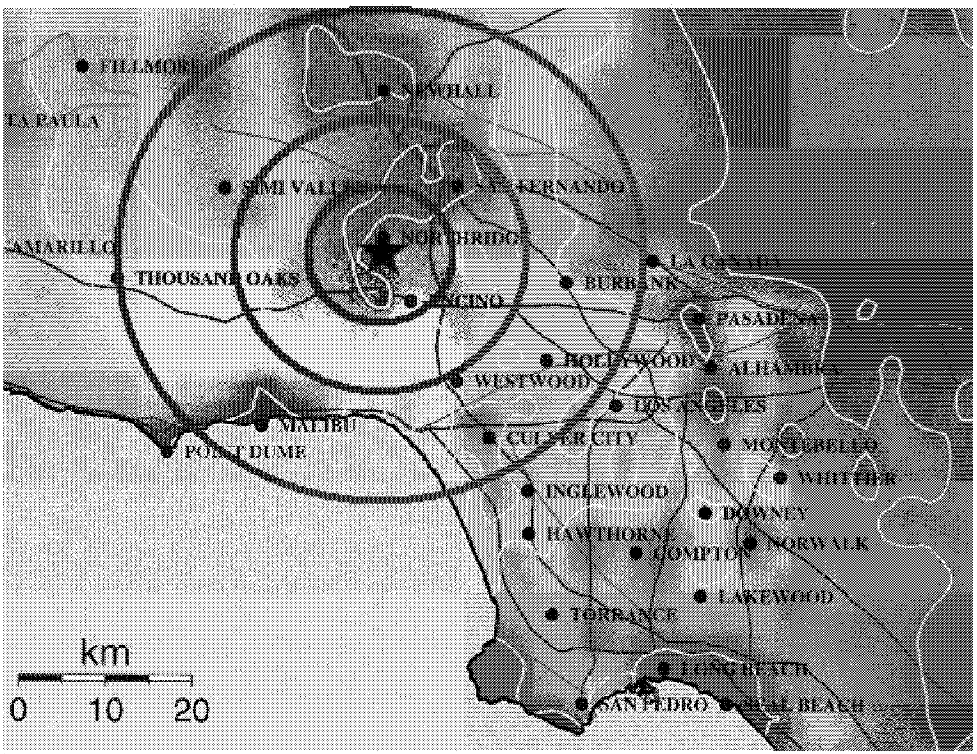


Figure 4 – Magnitude of ground shaking from the 1994 Northridge earthquake

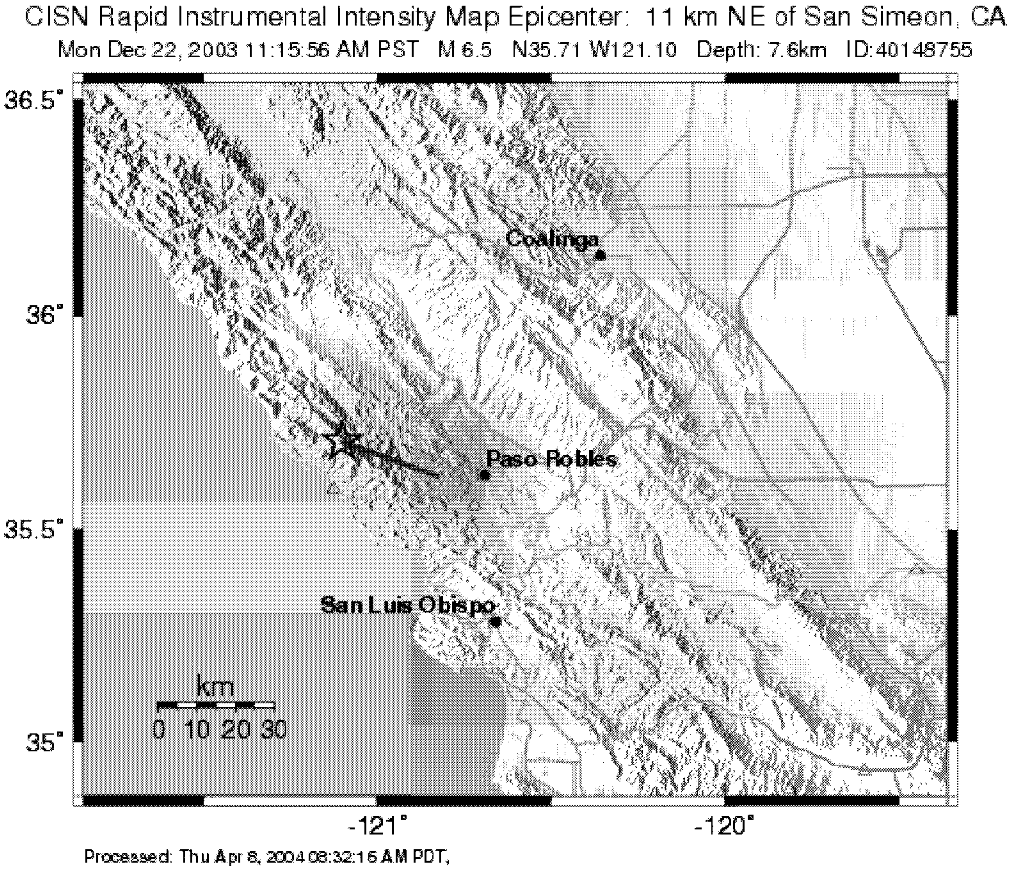
Following the 1994 Northridge earthquake, inspection crews used these types of techniques to focus reconnaissance efforts. While ultimately all of the potentially-damaged bridges were inspected and assessed by inspection teams, the lack of information about specific areas with the highest levels of ground shaking prevented them from undertaking a more rigorous and efficient process.

Figure 5 – Damage from the 1994 Northridge Earthquake

Significant advancements in sensor, telecommunications, and data processing technologies have led to the development of emergency response tools which use data from the statewide network of seismic instruments. Through the California Integrated Seismic Network (CISN), a cooperative project between federal and state government agencies, and university research institutions, efforts are being made to improve access to near real-time seismic information in California. CISN continuously monitors ground shaking throughout the state using its combined network of over 3000 seismic instruments from the University California San Diego Anza Network, University California Berkeley Digital Seismic Network, University California Berkeley Parkfield High-Resolution Borehole Seismic Network, California Geological Survey Strong Motion Instrumentation Program, USGS/Caltech Southern California Seismic Network and TriNet, USGS Northern California Seismic Network, USGS National Strong Motion Program, Pacific Gas and Electric, University of Nevada Reno Northern Nevada Seismic Network, University of Nevada Reno Southern Nevada Seismic Network, and the California Department of Water Resources . Following a seismic event, data is retrieved from the instruments, processed centrally, and disseminated via pager and email within minutes to engineers, seismologists, emergency responders, public information officers, and other personnel in critical state and local government agencies. These notifications provide the most essential seismic information for each event including the time, date, location, magnitude, epicenter and peak acceleration. Data that is collected is also catalogued and maintained for future reference by the earthquake engineering and earth science community.

Figure 6 Data Recorders and Other Strong Motion Sensor Recording Hardware

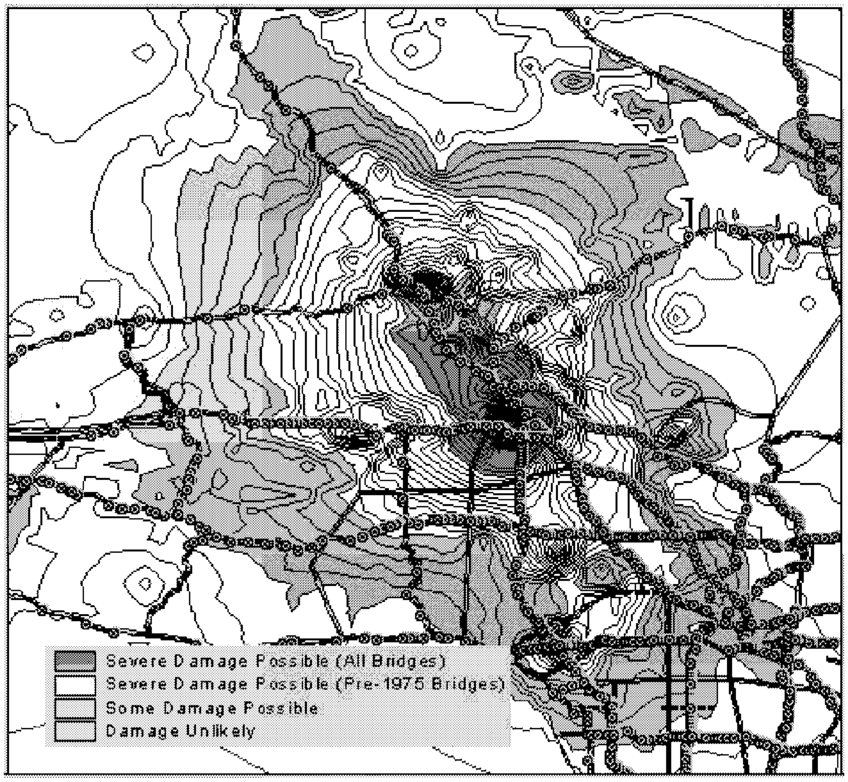
In the late 1990's, TriNet, a partnership between Caltech, the USGS, and CGS, developed "ShakeMaps," that graphically present the intensity of ground shaking based upon measurements from instrumented sites in the CISN. The ShakeMaps are made available via the internet within 5 to 10 minutes following an earthquake. The color-contour base map in Fig. 7 shows an example ShakeMap for the 2003 San Simeon Earthquake.



PERCEIVED SHAKING	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
POTENTIAL DAMAGE	none	none	none	Very light	Light	Moderate	Moderate/Heavy	Heavy	Very Heavy
PEAK ACC.(%g)	<.17	.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
PEAK VEL.(cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

<u>Figure 7 ShakeMap from the December 2003 San Simeon Earthquake</u>

Since the advent of the ShakeMaps, Caltrans and its partners have worked to identify opportunities to improve post-earthquake inspection prioritization methods. Currently, after notification of a significant seismic event by CISN, ShakeMaps are used to identify the regions of strongest ground shaking. Using GIS technology, state highway bridges are overlaid on the ShakeMap and a bridge inspection priority list is generated based on the level of ground shaking at each bridge site (See Figure 8).



Bridge Name	Bridge No.	PM	latitude	longitude	Dist	Co	Rte	SA (1s)	Potential Damage Status
ALISO CR CULVT	53 2634	R6.38	34.2683	-118.5183	7	LA	118	1.04	Severe Damage Possible (All Bridges)
CHIMINEAS AVE OC	53 2512	R6.23	34.2683	-118.5167	7	LA	118	1.04	Severe Damage Possible (All Bridges)
ETIWANDA AVE POC	53 2511	R6.03	34.2700	-118.5267	7	LA	118	1.00	Severe Damage Possible (All Bridges)
RESEDA BLVD OC	53 2510	R5.81	34.2767	-118.5300	7	LA	118	1.00	Severe Damage Possible (All Bridges)
WILBUR AVE OC	53 2509	R5.2	34.2750	-118.5450	7	LA	118	0.96	Severe Damage Possible (All Bridges)
TAMPA AVE OC	53 2647	R4.64	34.2733	-118.5467	7	LA	118	0.88	Severe Damage Possible (Pre-1975 Bridges)
LIMEKILN CANYON WA	53 2502S	R4.6	34.2667	-118.5483	7	LA	118	0.88	Severe Damage Possible (Pre-1975 Bridges)
LIMEKILN CANYON WA	53 2502K	R4.54	34.2667	-118.5483	7	LA	118	0.88	Severe Damage Possible (Pre-1975 Bridges)
HADDON AVE PUC	53 2175	R11.9	34.2683	-118.4350	7	LA	118	0.88	Severe Damage Possible (Pre-1975 Bridges)

Figure 8 – Example of ShakeMap with List of Potentially Damaged Bridges

While still under development at the time, the December 2003 San Simeon earthquake provided an opportunity to demonstrate the capabilities of this technology. Six minutes after the magnitude 6.5 earthquake occurred, pager and email notifications were made to emergency responders, including Caltrans staff. Within ten minutes, a preliminary ShakeMap was available on the Internet. Within 90 minutes a preliminary bridge inspection list had been generated and emailed to SMI for informational purposes.

Although used only as a secondary tool to supplement current standard post-earthquake inspection procedures during the San Simeon Earthquake, the promise of this technology was clearly shown. Caltrans Structure Maintenance and Investigations is working with the Division of Research and Innovation to develop enhancements in order to more fully integrate this tool into standard post-earthquake response practices. These enhancements are proposed through the addition of bridge fragility curves and recognition of bridge attributes including bridge type, span length, soil conditions, period, design ground motion level, etc. to further refine the bridge inspection prioritization process. Using this information, a “red-yellow-green” indicator of the likelihood of damage following an earthquake is envisioned to more precisely target post-earthquake bridge inspection activities.

TOLL BRIDGE POST-EARTHQUAKE DYNAMIC ANALYSIS MODELS

As part of Caltrans Seismic Retrofit program, ADINA dynamic analysis models were developed to perform nonlinear time-history analysis of the state's vital Toll bridges. Currently a contract is in place to standardize these models, which were created by in-house state engineers and a number of different engineering consultant firms. These models will be archived and maintained for future reference following a large seismic event. Utilizing pre-processing and post-processing software under development as part of this contract, the standardized models will allow Caltrans to quickly analyze these bridges using earthquake free field and downhole input records. Caltrans engineers will be able to use recorded input motion to validate and modify the models as necessary. Additionally the models can be used to predict regions of potential damage after a major earthquake. Caltrans Office of Earthquake Engineering will alert Structure Maintenance and Investigations of their findings, allowing post-earthquake inspection crews to focus their initial inspection activities on the most vulnerable locations of the bridge.

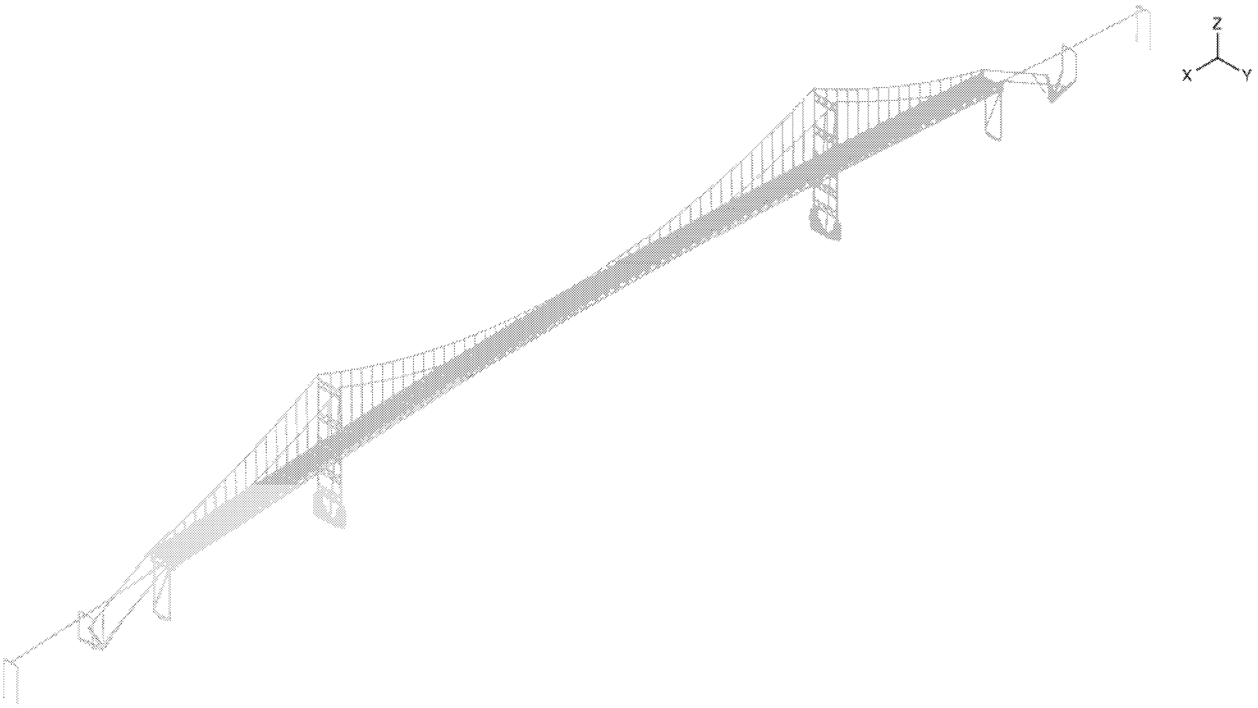


Figure 9 Graphic Representation of the Vincent Thomas Bridge ADINA Model

SEISMIC GATES

In lieu of seismic retrofit, or where seismic retrofit construction is pending, seismic gates have been installed at several bridges in rural Northern California to control traffic following a large earthquake (See Fig. 10). These gates are similar to railroad crossing gates and are controlled by strong motion sensors at the site to close the bridge in the event of strong ground shaking. The closure of the structure prevents public use of these bridges until a thorough post-event inspection can be completed. In addition to activating the gates, the strong motion sensors trigger notification of local traffic control personnel and bridge maintenance crews.

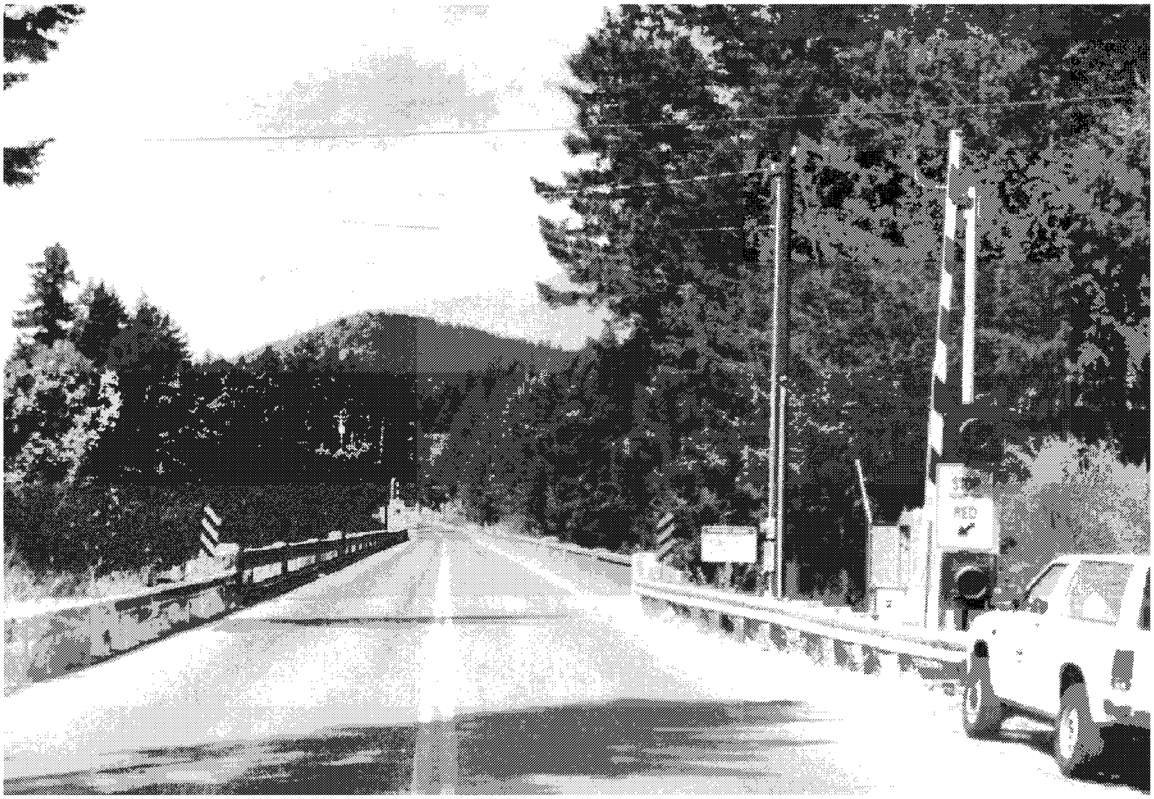


Figure 10 Seismic Gates at the Cedar Creek Bridge

HEALTH MONITORING

The new Benicia-Martinez Bridge, which is currently under construction on Interstate 680 in the Bay Area of Northern California, has been designated an "Important" bridge requiring post-earthquake serviceability. The design incorporates the use of light-weight concrete to limit seismic demands by reducing bridge mass. Due to lack of data on the short and long term behavior of large single cell box girder bridges constructed with high strength lightweight concrete, and the desire to collect seismic strong motion data, a health monitoring system has been integrated with that of the seismic strong motion instrumentation. Measurements will be made of the deformation of the superstructure, the condition of the prestressing tendons through acoustic sensing, and seismic demands placed on the bearings and unique mid-span hinge. This information will be transmitted to a central location for use by SMI for post-earthquake response, and for studies of the long term behavior of this unique bridge in the Caltrans inventory of highway bridges.

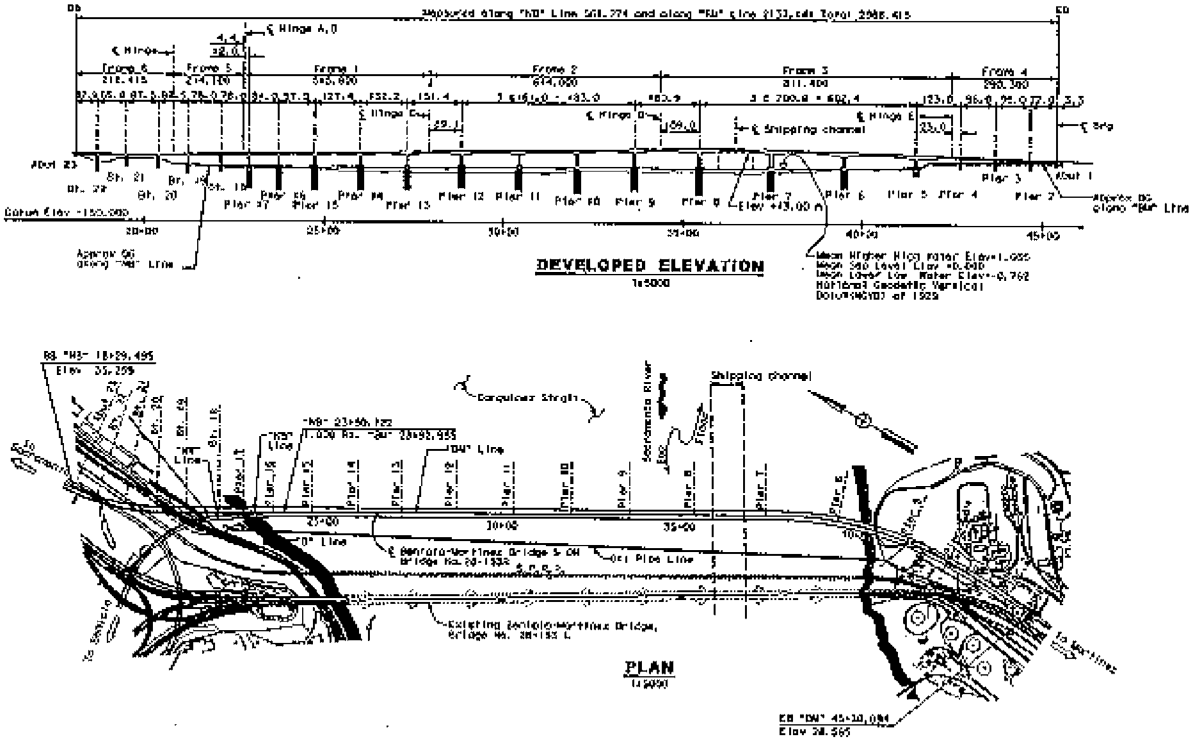


Figure 11 Benicia-Martinez Bridge Plan and Elevation Details

CONCLUSION

Caltrans has significantly expanded its inventory of bridges instrumented with strong motion sensors since the 1989 Loma Prieta Earthquake. Currently there are nearly seventy bridges, including all of the Toll Bridges, included in the CSMIP program. This represents a considerable improvement in Caltrans ability to capture ground and structural response recordings in order to perform post-earthquake assessment of the Department's hazard, analysis and design methodologies. In addition, as the network of strong motion recorders has expanded, Caltrans is working with its partners in other agencies and research institutions to use strong motion data to improve emergency response procedures and other uses. The potential of strong motion technology is clearly demonstrated by the initial implementation efforts outlined in this report with the promise of significant advances in the future.

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