BRIDGE INSTRUMENTATION AND POST-EARTHQUAKE EVALUATION OF BRIDGES

Patrick Hipley, P.E.
Seismic Technology Section
Office of Earthquake Engineering
California Department of Transportation

and

Moh Huang, Ph.D., P.E. and Anthony Shakal, Ph.D.
California Strong Motion Instrumentation Program
Division of Mines and Geology
California Department of Conservation

ABSTRACT

As the number of large civil structures instrumented for strong motion is increasing, efforts towards utilizing the earthquake data collected from these structures is also increasing. The studies are geared towards verifying seismic engineering design assumptions by comparing the theoretical models to the actual readings. Efforts to utilize the data ranging from simple comparison of the estimated structural period of vibration with the recorded free vibration, to complex comparisons of non-linear time-history models are underway. Many more studies are needed to take full advantage of this valuable data.

Accurately monitoring bridge movements during a large earthquake is necessary to advance our understanding of how these massive structures are affected by seismic input. Bridges of different structure types react differently to the same seismic wave patterns. Dynamic soil-structure interaction can be studied and theories can be verified or disproved based on the actual readings. Before strong motion sensors were placed at ground sites or on civil structures, theories were based on very little data. Therefore, the data collected from large earthquakes with these sensors are invaluable to the seismic engineering community.

The California Department of Transportation (Caltrans) and the California Strong Motion Instrumentation Program (CSMIP) of the California Department of Conservation's Division of Mines and Geology have instrumented more than 50 Caltrans bridges throughout the State since the 1989 Loma Prieta earthquake. In addition, CSMIP and Caltrans are installing more near-real-time stations at selected bridge sites in the State. Consequently, more near-real-time strong-motion data will be available quickly after an earthquake. These data provide information on ground shaking and response of the bridge structure, and are useful not only for improving seismic design practices but for post-earthquake damage evaluation of bridges. This paper describes the current status and future plan of the Caltrans/CSMIP bridge instrumentation project, and discusses quick application of strong-motion data to post-earthquake evaluations of bridges.

Cases of quick application of near-real-time data are presented and criteria for determining post-earthquake inspection of bridges are discussed.

INTRODUCTION

Since the 1989 Loma Prieta earthquake, a comprehensive program was initiated by the Department of Transportation (Caltrans) and the California Strong Motion Instrumentation Program (CSMIP) of the California Department of Conservation's Division of Mines and Geology to instrument more Caltrans bridges throughout the State. This bridge strong motion instrumentation program was in response to recommendations by the Governor's Board of Inquiry (Housner, 1990) that Caltrans implement comprehensive program of seismic instrumentation to provide measurements of the excitation and response of transportation structures during earthquakes. Caltrans accelerated this effort in 1993 and has instrumented about 10 bridge structures per year since that time.

Since the 1994 Northridge earthquake, CSMIP has developed a near-real-time strong motion monitoring system in which the strong-motion records are recovered and processed automatically right after an earthquake. This system has been installed for CSMIP stations in southern California under the TriNet project and at new and upgraded stations in other parts of the State. In total, TriNet, a joint project between CDMG/CSMIP, Caltech and USGS, funded by the Federal Emergency Management Agency (FEMA) through the California Office of Emergency Services (OES), will install 670 stations in southern California. In the event of potentially damaging earthquakes, TriNet will produce a map, called "ShakeMap", of ground motion distribution within minutes. The first prototype model of a ShakeMap product is discussed by Wald, et al. (1998) in this proceedings volume. These maps will include peak ground acceleration, peak ground velocity, spectral acceleration at 0.3, 1, and 3 seconds, and other ground motion parameters. The ground motion information will be useful for Caltrans to quickly determine where bridge inspection is needed and which areas may have bridge structures damaged.

The current status and future plan of the bridge instrumentation program is presented herein. Quick interpretation of the strong-motion data and the application of near-real-time data to post-earthquake evaluation of bridges are discussed. The near-real-time data plus the existing database of the bridges will lead to development of new tools for post-earthquake response which will eventually be incorporated into Caltrans post-earthquake investigation team procedure.

BRIDGE INSTRUMENTATION

The California Department of Transportation to date has 54 bridges instrumented for strong motion with the number of sensors per structure ranging from as few as 4 to as many as 38 sensors. This work is a cooperative effort between Caltrans and the California Division of Mines and Geology. The bridge structures chosen for instrumentation vary in size and type, and are located throughout California. The locations of these bridges are shown in Figure 1. They are listed in Table 1 which includes bridge name, station number, bridge number, post-mile, construction date, number of sensors installed and the instrumentation completion date. Most of

Table 1. CSMIP/Caltrans Bridge Strong Motion Instrumentation Installed as of 4/30/98

	Station Name	Station No.	Bridge No.	Post Mile	Const. Date	No. of Sensor	Instr. Date
	Bridges:						
1	Albion - Hwy 1/Salmon Creek Bridge	79683	10-134	01-MEM-1-43.00	1951	6	3/17/94
2	Arcata - Hwy 101/Murray Road Bridge	89708	04-170	01-HUM-101-R92.99	1964	12(9+FF)	4/6/95
3	Beaumont - I10/60 Interchange Bridge	12649	56-452F	08-RIV-10-6.67	1961	6	12/16/92
4	Belmont - I280 Pedestrian Bridge	58678	35-285	04-SM-280-10.56	1973	6	11/19/93
5	Benicia - Martinez Bridge	68682	28-153	04-CC-680-25.04	1962	9	3/2/94
6	Big Sur - Hwy 1/Pfeiffer Canyon Bridge	47729	44-60	05-MON-1-45.5	1968	18(15+FF)	4/3/96
7	Corona - I15/Hwy 91 Interchange Bridge	13705	56-586G	08-RIV-15-R41.57	1989	9	9/29/94
8	Cuyama - Hwy 166/Cuyama River Bridge	25758	51-66	05-SB-166-R69.94	1980	12(9+FF)	4/8/97
9	Devore - I15/215 Interchange Bridge	23650	54-783R	08-SBD-15-16.35	1969	6	12/18/92
10	El Centro - Hwy 8/Meloland Overpass	01336	58-215	11-IMP-8-43.6	1971	32(29+FF)	4/26/78
11	Eureka - Eureka Channel Bridge	89736	04-230	01-HUM-255-0.2	1971	12(9+FF)	4/9/96
12	Eureka - Middle Channel Bridge	89735	04-229	01-HUM-255-0.7	1971	9(6+FF)	4/12/96
13	Eureka - Samoa Channel Bridge	89686	04-228	01-HUM-255-1.2	1971	27(24+FF)	4/12/96
14	Half Moon Bay - Hwy 1/Tunitas Cr. Bridge	58754	35-31	04-SM-1-20.82	1962	9(6+FF)	5/22/97
15	Hayward - BART Elevated Section	58501	N/A	BART	1967	19(16+FF)	4/3/86
16	Hayward - Hwy 580/238 Interchange Bridge	58658	33-214L	04-ALA-580-30.80	1988	10(7+FF)	6/11/93
17	Hopland - Hwy 101/Railroad Bridge	69760	10-81	01-MEM-101-R9.53	1966	16(13+FF)	5/22/97
18	Jenner - Hwy 1/Russian River Bridge	69671	20-195	04-SON-1-19.72	1984	6	9/29/93
19	Klamath - Hwy 101/Klamath River Bridge	99710	01-28	01-DN-101-R4.04	1965	6	4/13/95
20	Lake Crowley - Hwy 395 Bridge	54730	47-48	09-MNO-395-13.9	1969	9(6+FF)	8/30/95
21	Los Angeles - I10/405 Interchange Bridge	24670	53-1630G	07-LA-405-29.43	1963	7	9/13/93
22	Los Angeles - I10/La Cienega Bridge	24704	53-2791	07-LA-10-8.8	1994	15	11/2/94
23	Los Angeles - I405/San Gabriel River Bridge	14690	53-1185	07-LA-405-0.02	1964	6	4/27/94
24	Los Angeles - Vincent Thomas Bridge	14406	53-1471	07-LA-47-0.86	1964	26	10/22/81
25	Mojave - Hwy 14/Railroad Bridge	34715	50-402R	09-KER-14-15.32	1973	12	3/22/95
26	Moorpark - Hwy 23/118 Bridge (Arroyo Simi)	24738	52-331L	07-VEN-023/118-21.0	1993	12(9+FF)	5/8/96
27	North Palm Springs - I10/62 Interchange Bridg	12666	56-474F	08-RIV-62-0.00	1962	7	6/30/93
28	Oakland - Hwy 580/13 Interchange Bridge	58656	33-347S	04-ALA-580-R39.15	1965	6	5/26/93
29	Oakland - Hwy 580/24 Interchange Bridge	58657	33-302H	04-ALA-580-45.23	1970	6	5/20/93
30	Palmdale - Hwy 14/Barrel Springs Bridge	24706	53-1794	07-LA-14-R57.37	1965	12(9+FF)	12/8/94
31	Parkfield - Hwy 46/Cholame Creek Bridge	36668	49-36	05-SLO-46-54.77	1979	6	8/4/93
32	Pasadena - Hwy 134/210 Interchange Bridge	24689	53-2318G	07-LA-134-R13.25	1974	9(6+FF)	4/21/94
33	Ridgecrest - Hwy 395/Brown Road Bridge	33742	50-340	09-KER-395-R25.08	1966	9(6+FF)	2/22/96
34	Rio Dell - Hwy 101/Painter Street Overpass	89324	04-236	01-HUM-101-R52.89	1976	20(17+FF)	9/29/77
35	Rohnert Park - Hwy 101 Bridge	68717	20-235	04-SON-101-13.88	1973	12(9+FF)	5/3/95
36	San Bernandino - I10/215 Interchange	23631	54-823G	08-SBD-215-4.05	1966	37(34+FF)	1/10/92
37	San Diego - Coronado Bridge	03679	57-857	11-SD-75-R20.49	1969	9	11/17/93
38	San Diego - I5/Hwy 52 Interchange Bridge	03731	57-520L	11-SD-5-25.91	1966	24(21+FF)	5/18/95
39	San Fernando - I210/Hwy 118 Bridge	24714	53-2102	07-LA-118/210-6.0	1973	36(33+FF)	4/17/96
40	San Francisco - Bay Bridge/ East	58633	33-25	04-ALA-80-0.0	1936	9	2/28/93
41	San Francisco - Bay Bridge/West	58632	34-3	04-SF-80-5.6	1936	6	2/28/93
42	San Francisco Bay - Dumbarton Bridge	58596	35-38	04-SM-84-29.0	1982	32(26+2FF)	6/10/87
43	San Francisco Bay - San Mateo Bridge	58677	35-54	04-SM-92-14.44	1967	6	10/29/93
44	San Juan Bautista - Hwy 101/156 Overpass	47315	43-31	05-SBT-156-3.02	1958	12	5/24/77
45	San Simeon - Hwy 1/San Simeon Creek Bridg	37728	49-46	05-SLO-1-52.92	1984	12(9+FF)	9/6/95
46	Santa Barbara - San Roque Canyon Birgde	25749	51-104	05-SB-192-1.77	1984	9(6+FF)	10/24/96
47	Santa Clara- Hwy 237/Alviso Overpass	57748	34-470K	04-SCL-237-6.10	1994	12(9+FF)	10/25/95
48	Santa Clara- Hwy 237/Alviso Overpass	57748	34-470L	04-SCL-237-6.10	1994	9	10/25/95
49	South San Francisco - Sierra Point Overpass	58536	35-130	04-SM-101-23.7	1957	16(13+FF)	12/5/85
50	Sylmar - I5/14 Interchange Bridge	24694	53-2795F	07-LA-5-24.5	1994	38(35+FF)	12/20/95
51	Sylmar - I5/14 Interchange Bridge	24694	53-2797F	07-LA-5-24.5	1994	4	12/20/95
52	Truckee - I80/Truckee River Bridge	76741	17-58L	03-NEV-80-20.23	1989	8(5+FF)	10/24/95
53	Ventura - Hwy 101/Telephone Rd Bridge	25725	52-214L	07-VEN-101-R26	1961	12(9+FF)	5/5/95
54	Watsonville - Hwy 1/Struve Slough Bridge	47707	36-88R	04-SCR-1-R1.59	1990	9(6+FF)	11/23/94
	Geotechnical Arrays:						
1	Los Angeles - I10/La Cienega Geotechnical Ar	24703	N/A	07-LA-10-8.8	1994	9(2Dwns)	12/15/94
2	Eureka - Geotechnical Array	89734	N/A	01-HUM-255-1.2	1997	15(4Dwns)	5/16/97

the efforts are concentrated in the two large urban areas of Los Angeles and the San Francisco Bay Area.

Parallel geotechnical studies are underway to place deep downhole sensor arrays at various depths. Geotechnical downhole arrays are needed to analyze the soil column movement from a deep source and to better predict the surface movement from earthquakes. The ground motion varies from site to site and a large database of site conditions is needed before we can correlate soil and structural models. The downhole arrays are in the early stages but will be located throughout the State. Since geotechnical engineers will predict the site specific ground motions, the bridge engineers will need to work closely with the geotechnical engineers to fully understand all the assumptions and probabilities associated with the predictions. The actual downhole sensor readings will better our understanding of complex geologic vibrations.

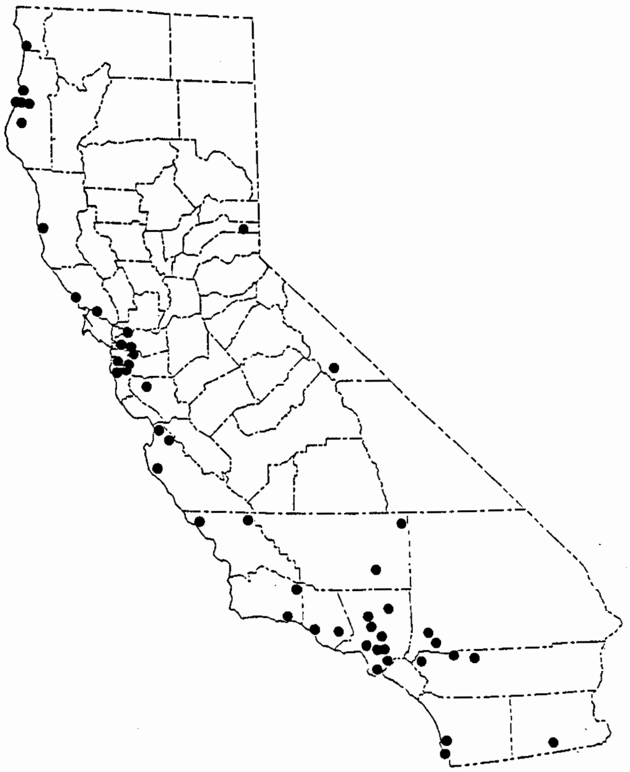

Figure 1. Locations of bridges instrumented with strong-motion sensors under the Caltrans/CSMIP Bridge Instrumentation Project.

Objectives of Bridge Instrumentation

The long-term goals of the bridge instrumentation are to record strong-motion data to (a) improve engineering design codes and practices, and (b) assess and mitigate the hazards posed by existing bridges. Strong-motion data from instrumented bridges are needed because the data provide critically needed information on the behavior of bridges at damaging levels of ground motion, and on the soil-structure interaction effects on the response of these structures. Due to the complexity of the response of bridges, which are affected by numerous structural elements with great nonlinearity, (e.g., abutments, hinges, soil and foundation pile interactions) nonlinear bridge response to damaging levels of ground shaking may not be reliably predicted using available analytical modeling techniques. Recorded data can be analyzed to verify these techniques and to advance state-of-the-art knowledge on the seismic performance of bridges.

The bridge strong motion instrumentation utilizes force-balance accelerometers that are designed to give readings up to 4g. The dynamic range of the recorders is also wide enough to measure low level vibrations from light shaking, which may be used to predict the movement that will occur when there is strong shaking. The sensors are placed on the bridges to measure seismic movements as they relate to the structural dynamic models. Enough sensors are placed to record the transverse mode shapes of the structure and the longitudinal motion of selected superstructure frame. A free-field tri-axial sensor package is placed at each site to measure the input motion to the structure. The free-field instrument is placed as far as practical away from the influence of any structure such as the bridge, a building, the approach embankment, etc., to avoid anomalous inputs. The free-field is placed on a rock outcrop if one is available.

There are basically three types of instrumentation plans: (a) light, (b) moderate, and (c) full. Typically, light instrumentation has six to nine sensors, moderate instrumentation has 10 to 24 sensors, and full instrumentation has 25 or more sensors. In general, the locations of sensors are planned primarily based on past experience in instrumenting bridges and recommendations from researchers who studied strong-motion data from instrumented bridges. The guidelines for instrumentation of highway bridges developed by Rojahn and Raggett (1981) are also considered. The overall goal of the instrumentation plan is to measure the seismic input motion and the response of the bridge structure. Specific measurements for each instrumentation plan are described as follows:

(a) <u>light instrumentation</u>. One of abutments and one of the columns are instrumented. Free-field sensors are included if it is feasible. An example is shown in Figure 2.

(b) <u>moderate instrumentation</u>. Several locations on the deck (to allow determination of the first transverse mode shape), the abutment, and a reference free-field site are instrumented. Special features of the bridge structure such as skewed, short columns, hinges, and soft sites are considered in the instrumentation plan.

(c) <u>full instrumentation</u>. This plan includes sensors to measure motions at both abutments, and at the base and the top of columns. In addition, a full instrumentation plan will measure lateral, vertical and torsional motions of the deck, relative motions across the hinges and the free-field motion. An example is shown in Figure 3. For major structures, like toll bridges in California, in which the structure spans different geologic conditions and much of the structure's mass is in the substructure, as many sensors as practical are installed at the foundations, and at locations as deep as possible such as at the pile tip in

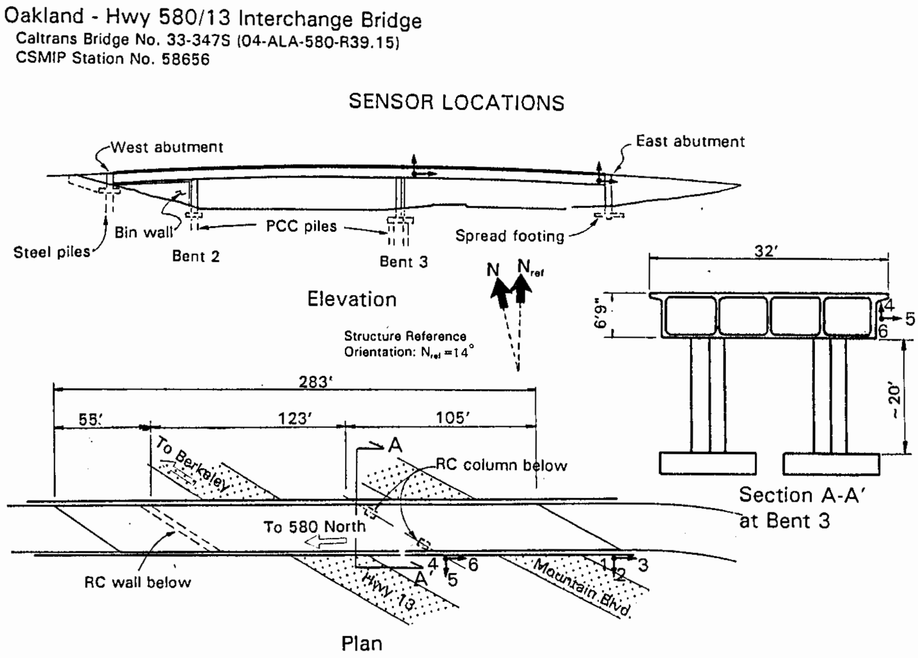

Figure 2. Sensor locations on Highway 580/13 Interchange Bridge in Oakland, which is an example of a light instrumentation plan.

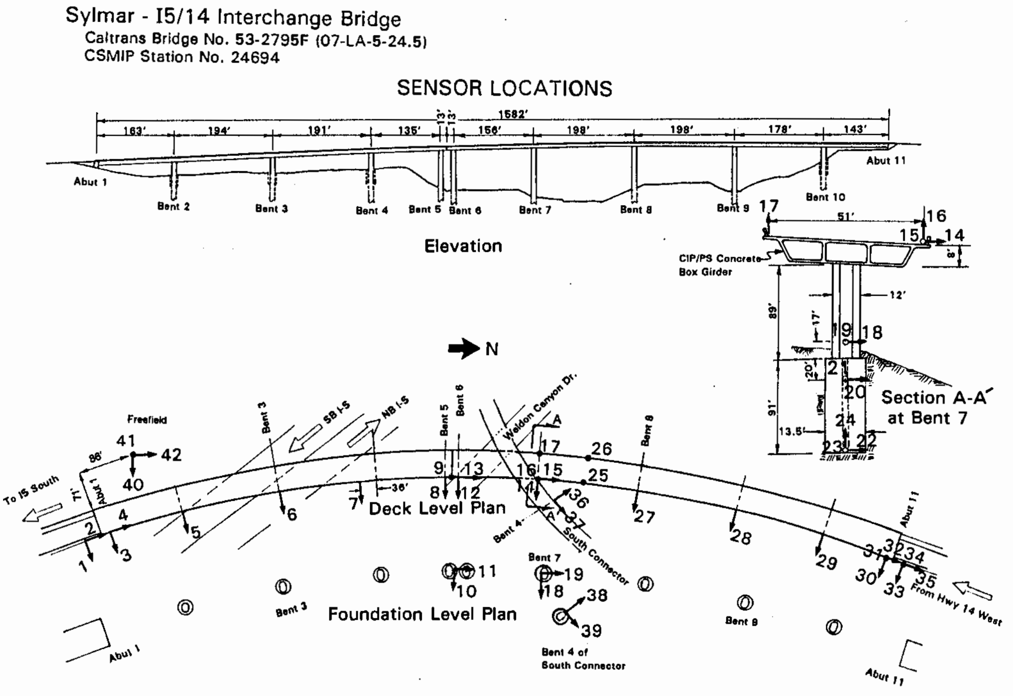

Figure 3. Sensor locations on Interstate 5/14 Interchange Bridge in Sylmar, which is an example of a full instrumentation plan.

the rock. The objectives are to measure differential ground input motions to the bridge and the soil-foundation-structure interaction effects.

Although it is always the case that only a limited number of sensors are available, the final sensor locations are selected optimally to achieve the above specific objectives and to allow determination of important dynamic characteristics of the bridge from strong-motion records.

Selection of Bridges for Instrumentation

The California Department of Transportation has over 12,000 bridges under its jurisdiction and it is not possible to instrument every bridge for strong motion. The bridge sites chosen are located throughout California to take advantage of the probability of having a structure close to an epicentral region. Many of the recent strong earthquakes are on newly discovered faults, so knowing where the next earthquake will be quite a challenge. The greater the coverage is the greater the chances are for recording the near source shaking.

Many of the selected Caltrans sites are in the large metropolitan areas. These areas happen to be in some of the highest seismic regions. A large percentage of the population lives in these metropolitan areas, thus a majority of large interchanges and other overcrossings are in big cities. Since life safety is the primary goal of bridge design and seismic retrofit, a great effort is placed on understanding of bridge response to large earthquakes in these areas. An examination of the Caltrans bridge sites having strong motion sensors will reflect these two philosophies, displaying a widely spread network with concentrations in the large urban regions.

Another tool used to determine the most prudent locations in California for bridge instrumentation is the earthquake probabilistic studies by the California Division of Mines and Geology and the U.S. Geological Survey that include mapping of known earthquake epicenters and faults. From these studies it is estimated that certain locations have a higher probability of experiencing strong shaking. These "hot spots" are where most of Caltrans instrumented structures are located.

A variety of bridge structure types are chosen for instrumentation to learn about the seismic responses of different bridge structures. It is hoped that lessons learned from an instrumented bridge can be applied to other bridges of similar type. The most common bridge type in California is the concrete box girder structure. Most of the bridges instrumented are of this type. Other types of bridges such as steel girder, truss structures, orthotropic girder, and pre-cast concrete are also instrumented. A variety of bridges that have multi-column, single-column or pier wall bents have been instrumented. In Santa Clara, two bridges at the same interchange, one with single-column and the other with multi-column bents, were instrumented to study the response of different structures to the same input ground motions.

Along with trying to understand the structure vibration mode shapes in an earthquake, components studies are in place to study individual aspects of bridge dynamics. These studies include the opening and closing of in-span hinges, the movement of superstructure over the abutments, the top and bottom relative deflection of a column, pile tip and pile cap relative motions, and so on.

The bridge instrumentation process begins with the study of the as-built plans to understand the key seismic response issues for the bridge structure. The most effective instrumentation layout is developed given the number of sensors allotted for the bridge. The instrumentation plan is often developed cooperatively by CSMIP and Caltrans. For toll bridges, the proposed sensor locations are also reviewed by Caltrans engineering consultants who performed the seismic vulnerability study of that bridge. CSMIP engineers and technical operations staff accompany Caltrans engineers and District field staff to the bridge site to finalize details of the actual installation. Finally, the bridge is instrumented by CSMIP field operation staff with logistical support of Caltrans District staff. For toll bridges, a slightly different process is used. For these bridges, the instrumentation plan with cabling runs and equipment enclosures was developed by Caltrans and CSMIP staff, and is incorporated as part of the retrofit work. After the installation, CSMIP staff then maintain the instrumentation, and recover and process the records after an earthquake.

Currently, the bridge instrumentation program has several elements. They include instrumentations of regular highway bridges, downhole arrays, toll bridges and other transportation facilities.

(1) Bridge Instrumentation. This element includes light, moderate and full instrumentation of regular highway bridges. Under this project, various types of bridges located near the major faults have been instrumented. These bridges range from a straight 2-span bridge to a multi-span curved bridge. Some are newly-constructed, e.g., the Interstate 5/Highway 14 Interchange bridge, and some have been retrofitted, e.g., the Interstate 210/118 Interchange bridge.

(2) Downhole Instrumentation. Caltrans is placing geotechnical downhole arrays in various locations throughout the State to study the soil column motion and amplification caused by input from the deep "rock-like" material. Two geotechnical downhole arrays, i.e., La Cienega Array and Eureka Array, have been installed and have recorded several small earthquakes. In addition to these two arrays, this project will install downhole array sensors at sites near major retrofit bridges. Some of the arrays may have only one downhole tri-axial sensor package and one ground surface package; some will have up to ten downhole units at various depths. At these downhole sites, the soil has been characterized very extensively by using P-S suspension logs, soil sampling, E-logs, cross-hole or downhole velocity measurements, etc. The recorded data will allow better understanding of site responses at different levels of shaking and the ground motion at deep material on which the bridge piles are founded.

(3) Toll Bridge Instrumentation. Work is currently underway to instrument all of California's toll bridges for strong motion. Some of the toll bridges are currently lightly instrumented and more sensors will be added. Instrumentation plans have been developed so that the instrumentation can be incorporated as part of the retrofit work. The six existing toll bridges in Table 2 and three planned toll bridges, i.e., new Bay Bridge, new Carquinez Bridge and new Benicia Bridge, will be extensively instrumented. As many as 115 sensors will be installed on and near the bridge to

measure the bedrock motions, free-field ground motions, substructure and superstructure responses in future earthquakes. The records will be used to verify the complex analytical models used in the seismic retrofit analyses of these bridges.

Table 2. Caltrans/CSMIP Instrumentation of Existing Toll Bridges

Name of Bridge	Type/Length of Main Structure	Total Length	Year of Completion	No. of Sensors Planned
Benicia - Martinez Bridge	steel truss, 4,884'	1.2 miles	1962	90
Vallejo - Carquinez Bridge (East)	steel truss, 3,350'	1.0 mile	1958	72
Richmond - San Rafael Bridge	steel truss and plate girder, 18,483'	4.0 miles	1956	90
San Francisco - Oakland Bay Bridge (West)	steel suspension, 10,051'	2.0 miles	1936	75
San Mateo - Hayward Bridge and Trestle	steel box girder, 9,650'	6.8 miles	1967	115
San Diego - Coronado Bridge	steel girder and box girder, 7,423'	1.6 miles	1969	96

(4) Instrumentation of Other Transportation Facilities The Posey and Webster Street underground tubes in Oakland will be instrumented as part of the retrofit effort. The tubes provide access from Oakland to Alameda and travel under the harbor waterway. The tubes were constructed by sinking the sections into the water and then placing enough soil on top of them to overcome the buoyancy forces. The retrofit will include stone column installations and soil densification to prevent liquefaction. A downhole geotechnical array is also planned at this site to study liquefaction. The strong-motion sensors will also used to trigger warning signs that will close the tubes after a big event. In another effort, seismic gates similar to railroad crossing gates are placed in very remote locations in northern California to close the bridge after a large earthquake. When the ground motion exceeds a certain level, the instrumentation system activates the closure of the gate. The bridges will remain closed until structural integrity assessment by the local maintenance personnel are completed. Sensors are also placed on these bridges to help with the study on the bridge structure health monitoring.

POST-EARTHQUAKE EVALUATION OF BRIDGES

Many of the instrumented bridges have a recording system from which the recorded data can be recovered via the phone lines and processed in Sacramento immediately after an event. The data can be used by the Caltrans engineers to quickly assess the structural integrity of that individual bridge. However, for the bridges that are not instrumented the engineers can utilize the near-real-time data recorded at free-field sites in the area. From the characteristics of that bridge and the ground motion information, the earthquake force experienced by that bridge can be estimated. Based on the design information and the experience from past earthquakes, Caltrans post-earthquake response team can then determine whether inspection of that bridge is needed.

Near-Real-Time Strong-Motion Data

Developments in accelerographic instruments and communication technology have made possible significant advances in the monitoring and reporting of earthquake strong motion. Since 1995 CSMIP has developed and implemented a system for near-real-time data recovery from strong-motion stations (Shakal, et al., 1995 and Shakal, et al., 1997). The data recovered are automatically processed to produce the ground motion parameters that are most useful for engineering assessment of the earthquake impact. As an example of the near-real-time data, Figures 4 and 5 show the record recovered from the Mammoth Lakes station, approximately 8 km west of the epicenter of a magnitude 3.6 earthquake that occurred on January 3, 1998. Three components of band-passed acceleration, velocity and displacement, and the acceleration response spectra were automatically calculated and plotted after the event.

The TriNet project will produce quick maps "ShakeMap" of potentially damaging ground shaking within minutes of a damaging earthquake. By year 2002, there will be 670 stations in southern California that records the ground motions. The "ShakeMap" will give contoured maps of the ground shaking parameters for the affected areas and the heavily impacted areas can be determined from these maps. The parameters for the ground shaking include peak ground acceleration, velocity, and spectral acceleration at 0.3, 1 and 3 seconds. The maps are still under development to meet a variety of needs, however, experimental maps are now available on the Worldwide Web *http://www.trinet.org* after an event. Details on the early development of these maps are presented in a paper in this proceeding volume (Wald, et al., 1998).

The TriNet ShakeMap will be useful for quickly determination of which areas experienced damaging ground shakings. In addition, the ground motion records in those areas affected can be quickly studied and compared with the design spectra to determine whether inspection of the bridges in the area is needed. For those bridges that are instrumented, the recorded response can be quickly interpreted without complex analyses to facilitate the determination.

Post-Earthquake Response

In California and Nevada, locations and magnitudes of recent earthquakes are available on Worldwide Web *http://quake.wr.usgs.gov* right after the event. Response personnel can also receive the information from paging systems. Generally, earthquakes smaller than 5 do not cause damages to engineering structures. Therefore, the response personnel will only need to proceed further for earthquakes larger than 5.

Currently, Caltrans has a post-earthquake investigation team procedure. In the procedure, the team coordinator will determine the area of damage and a list of bridges to be investigated based on the magnitude and location of the earthquake. A GIS-based software and the database of bridges are used to create the map and the list. This procedure can be expanded to include the ground shaking information produced by TriNet. Depending on the year of design, design

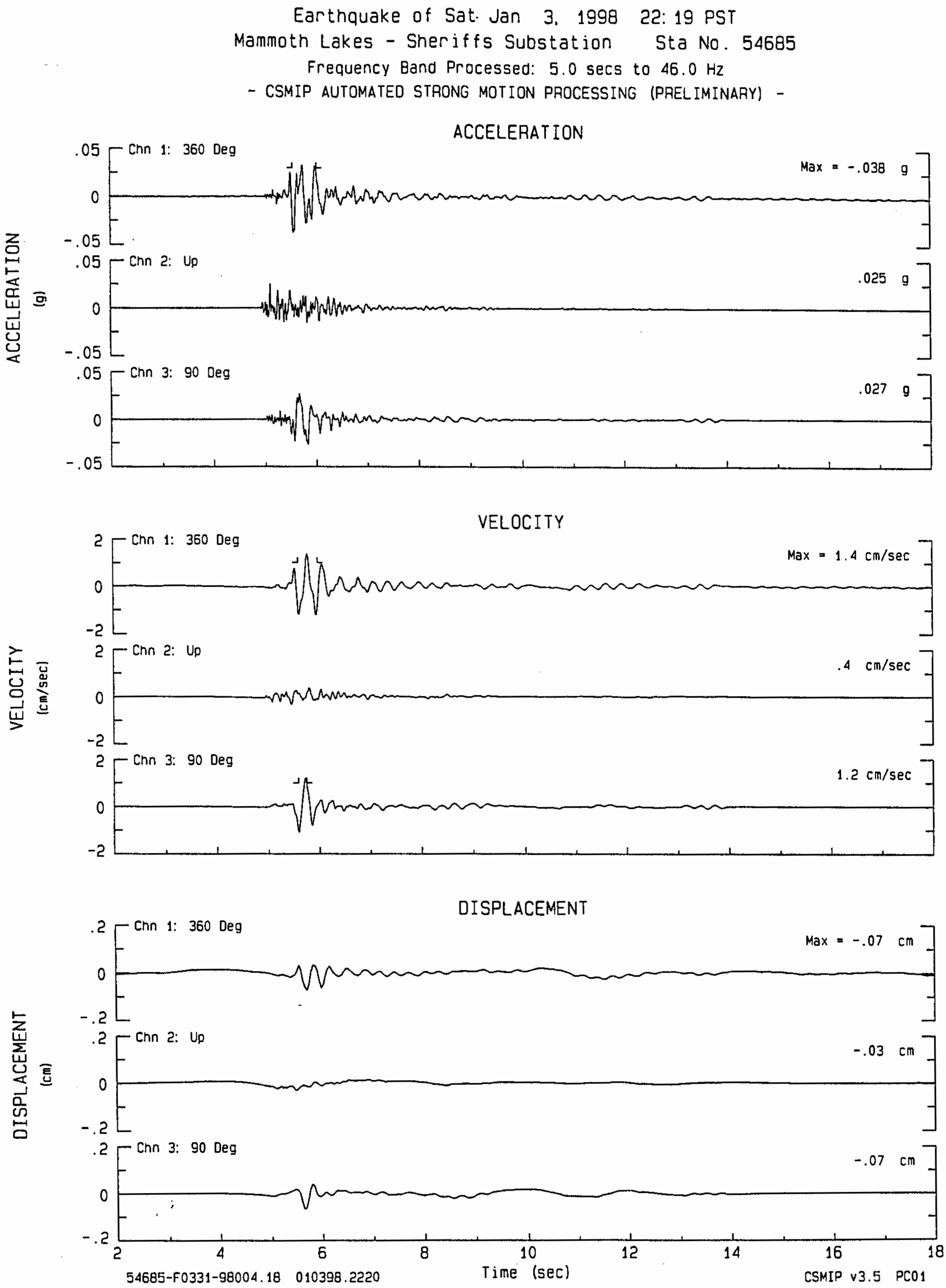

Figure 4. Near-real-time data - three components of band-passes acceleration, velocity and displacement at Mammoth Lakes from the magnitude 3.6 earthquake of January 3, 1998.

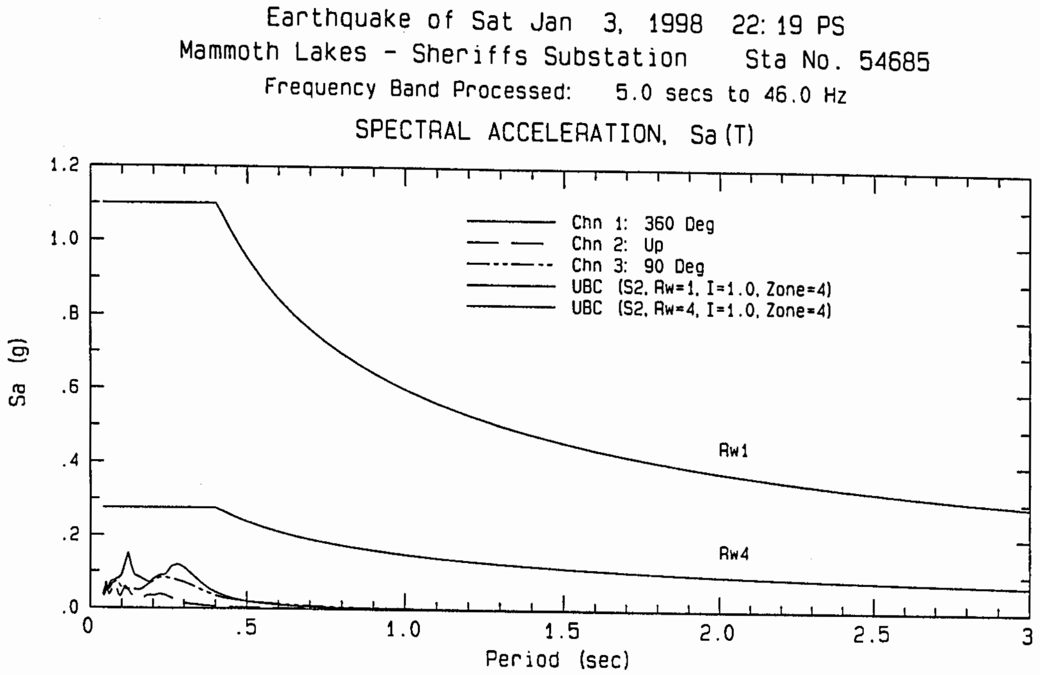

Figure 5. Near-real-time data - three components of spectral acceleration (5% damping) at Mammoth Lakes from the Magnitude 3.6 earthquake of January 3, 1998. The design spectra from the 1994 UBC are plotted for convenient comparison.

forces (ARS curve used in design) and the characteristics of each bridge, Caltrans engineers can determine whether the earthquake force is larger than the design force for each bridge.

One example of post-earthquake evaluation using near-time-data is the Highway 395 near Lake Crowley. The bridge, designed in 1965, is a 2-span, 203 feet long concrete box girder bridge (Figure 6). The substructure consists of a two-column bent and diaphragm abutments supported on spread footings. The bridge was instrumented moderately in 1995 with 9 accelerometers. The locations of these sensors, including 3 at a free-field site and 6 on the bridge structure are shown in Figure 7. The magnitude 5.1 earthquake occurred on June 8, 1998 approximately 5 km west of the bridge. The maximum recorded acceleration was 0.20 g at the free-field and 0.24 g on the bridge (Figure 8).

One can quickly study the acceleration(Figure 8), velocity and displacement (Figure 9) time histories and determine that the bridge has a period of about 0.2 second in the transverse direction and the relative displacement between the top and bottom of column at the central bent is very small. The spectral acceleration of the ground motion at the free-field site level is shown in Figure 10. The force level at 0.2 second is about 0.4 g, which is about one-fourth of the force level, 1.6 g (A=0.5g), from the ARS curve in Figure 11 (Caltrans, 1990). One can conclude that the earthquake force was not large enough to damage the bridge.

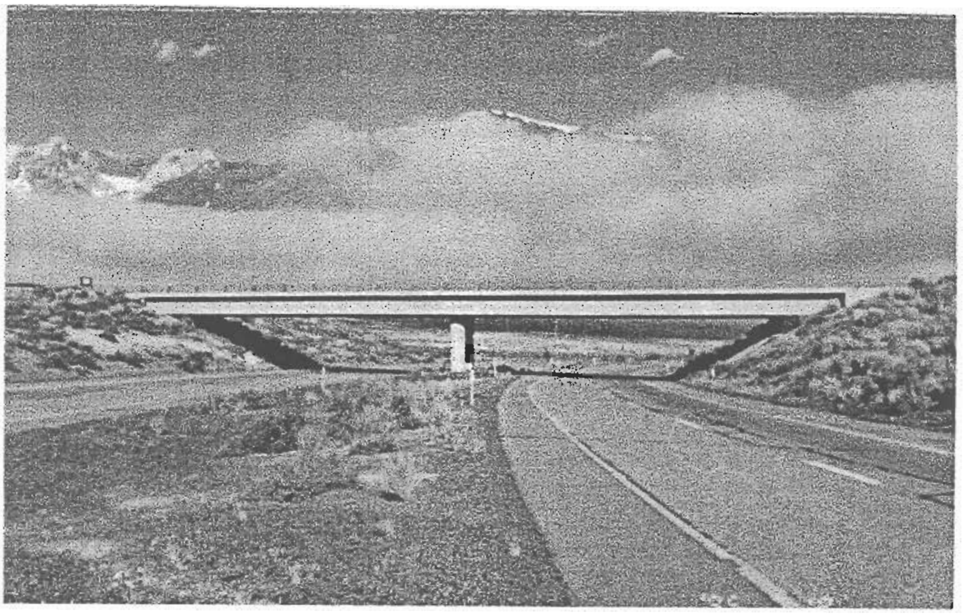

Figure 6. Picture of the Highway 395 Bridge near Lake Crowley. The bridge is a two-span, 203 feet long concrete box girder structure with a two-column bent.

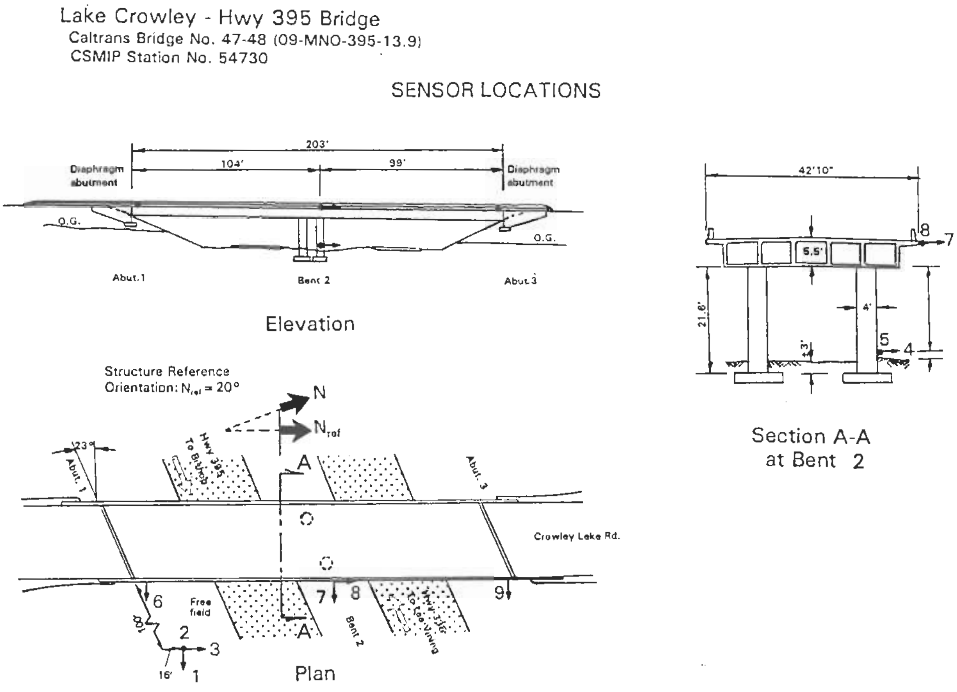

Figure 7. Sensor locations on the Highway 395 Bridge near Lake Crowley. The instrumentation consists of 6 sensors on the bridge and 3 sensors at a reference free-field site.

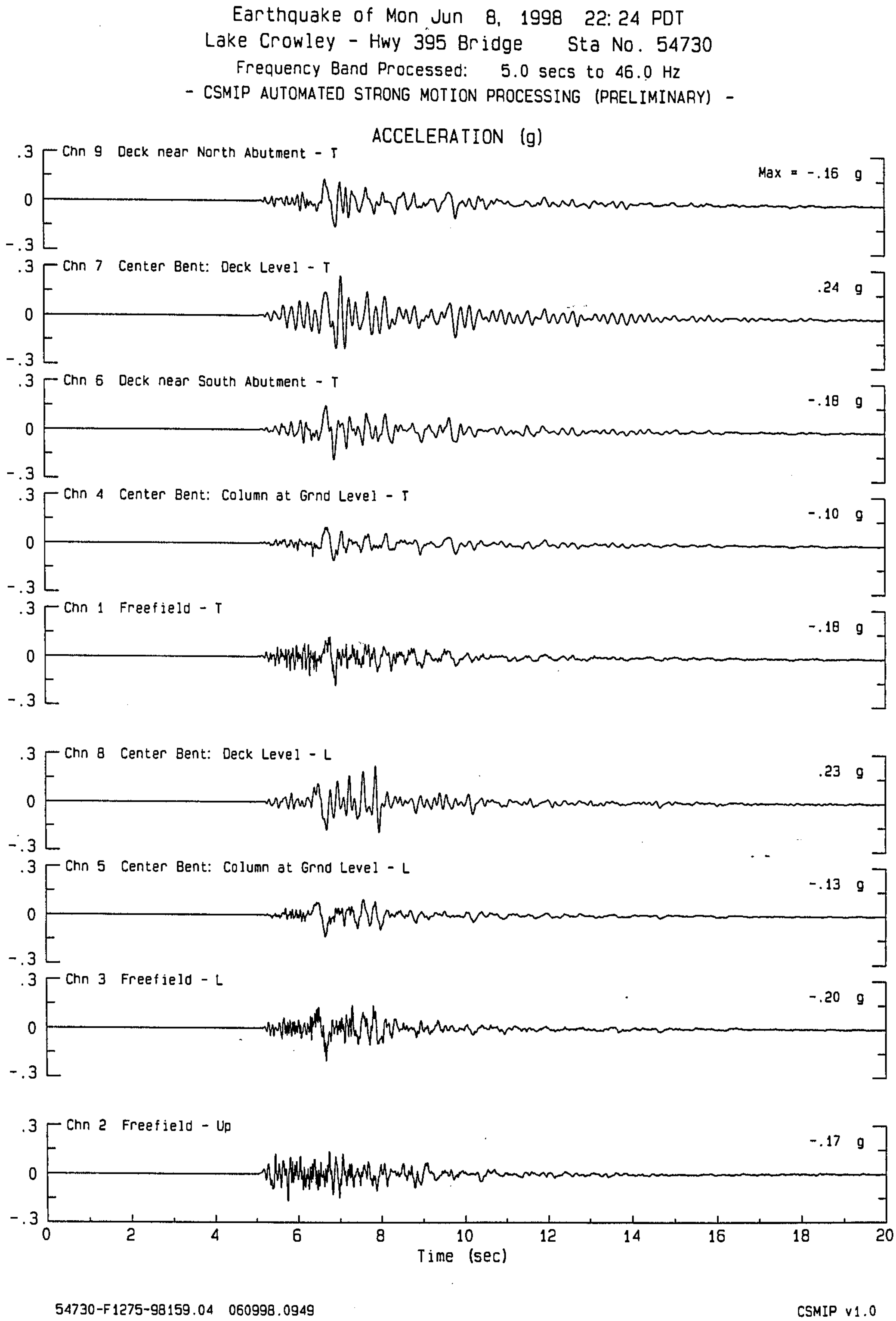

Figure 8. Acceleration records obtained at the Highway 395 Bridge near Lake Crowley from the magnitude 5.1 earthquake of June 8, 1998, about 5 km west of the bridge.

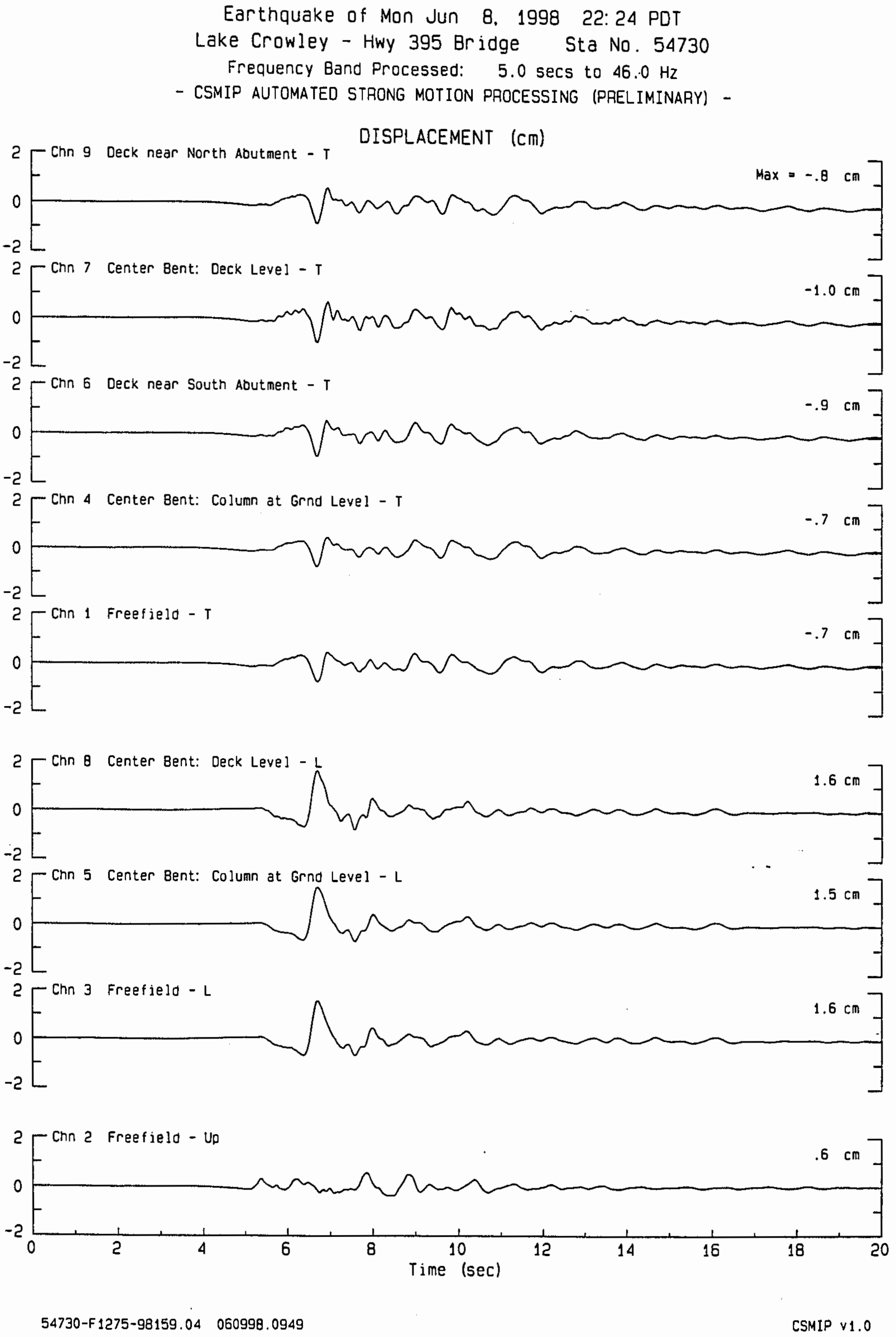

Figure 9. Computed displacement (absoulte) from acceleration records obtained at the Highway 395 Bridge near Lake Crowley from the magnitude 5.1 earthquake of June 8, 1998, about 5 km west of the bridge.

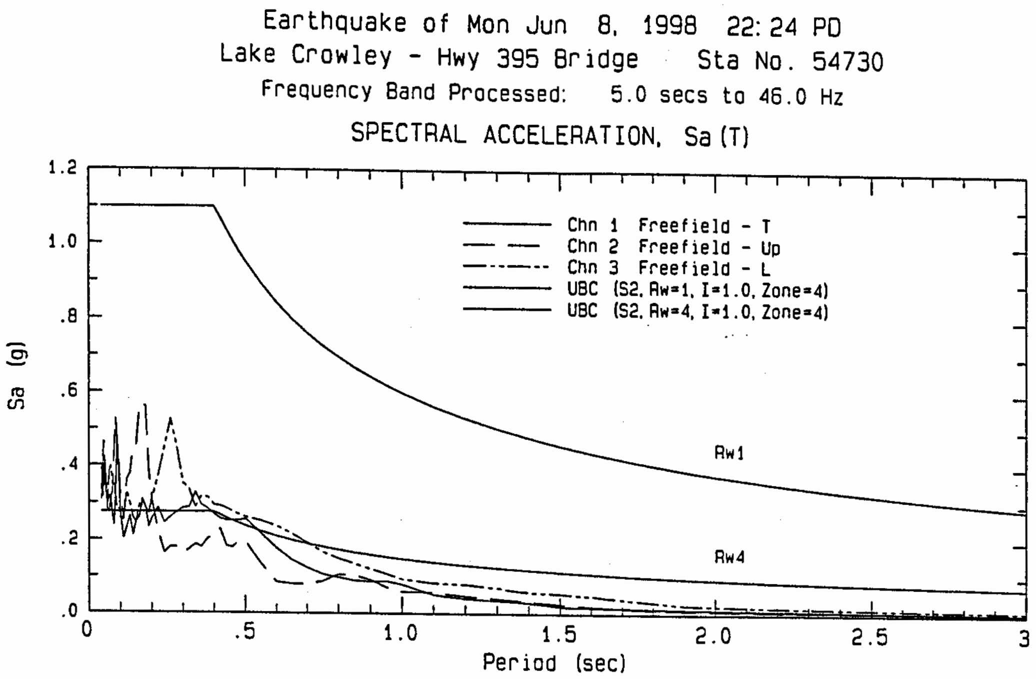

Figure 10. Spectral acceleration (5% damping) for the three-components of ground motion at the free-field site for the Highway 395 Bridge near Lake Crowley from the Magnitude 5.1 earthquake of June 8, 1998.

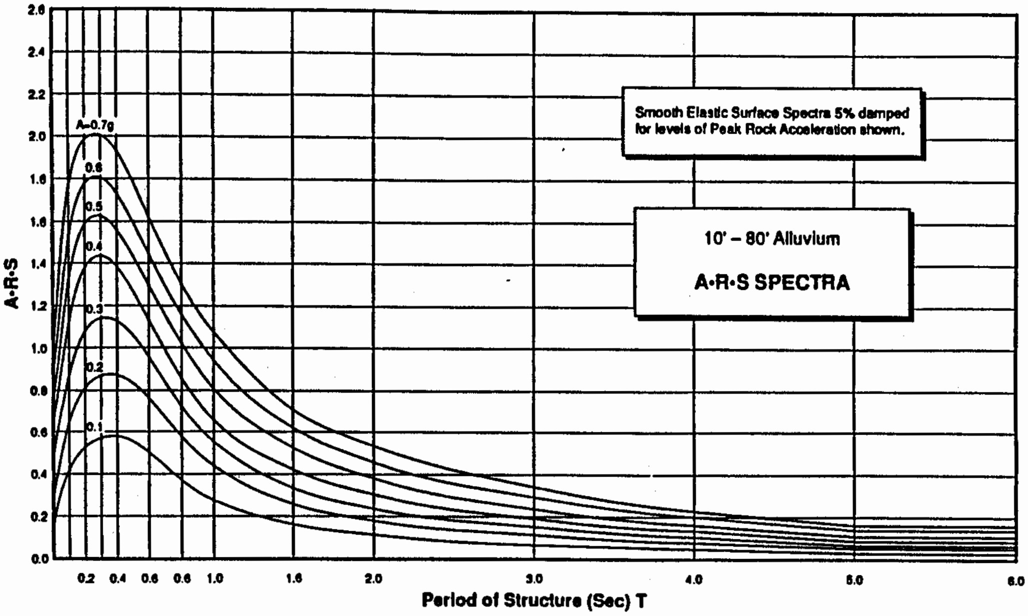

Figure 11. Design spectra (ARS curves) for sites with 10 to 80 feet of alluvium used by Caltrans in design of new bridges and retrofit of exisitng bridges.

Offshore Eureka Earthquake of 1994

Another example is the magnitude 7.2 earthquake that occurred offshore of Eureka on September 1, 1994, which is the first event for which the near-real-time data were applied for post-earthquake response. Although the earthquake was located 145 km offshore of Eureka, California, a large magnitude earthquake like this is expected to generate a lot of energy at long periods, which may have effects on long-period bridges like the Humboldt Bay Bridge. This earthquake was recorded by the near-real-time instruments installed at the Humboldt Bay Bridge. Peak motions at the bridge abutment was 0.03 g in acceleration and 4 cm/sec in velocity(CSMIP, 1994). The near-real-time data from the bridge and other stations were distributed to Caltrans post-earthquake response team after the earthquake. The information allowed Caltrans engineers to rapidly decide not to send inspectors to the Eureka area, 500 miles from Sacramento, to inspect their bridges in the area, despite the occurrence of an earthquake as large as magnitude 7.2.

Criteria for Post-Earthquake Inspection of Bridges

After a damaging earthquake occurs, TriNet ShakeMaps will provide ground shaking information within minutes of the event. For bridges that collapse during the earthquake, that information will probably be reported by the California Highway Patrol or the local newscasters. However, for the bridges that are damaged and need to be inspected to determine the extent of damage, TriNet ground shaking information will help Caltrans engineers in determining where and which bridges need to be inspected. To facilitate the inspection efforts, it is essential that there is a correlation between the ground shaking and the performance of different types of bridges. The 1994 Northridge earthquake provided an opportunity for studying the relationship between bridge performance and ground motion. The bridges can be grouped into various types of structures bridges, and their performances can be correlated with the ground motion. Fragility curves for each type of bridge structure can be derived in a statistical sense. However, more data are needed from different earthquakes to obtain more reliable empirical fragility curves, and the spectral acceleration values at 0.3, 1 and 3.0 seconds seem to be better parameters than the peak ground acceleration in indicating the effects of ground motion on structures.

One of the simple screening criteria for bridge inspection can be based on the ratio of the earthquake forces inferred from the ground motion data and the design forces used in the working stress design. In designing new bridges and retrofit of existing bridge, the design forces are used to be obtained by dividing the expected seismic forces from the ARS curves by the appropriate factor, Z, as shown in Figure 12 (Caltrans, 1990). One can expect that individual structural members would yield when the earthquake forces exceed the design forces used for those members. The members would have cracked if they yield and therefore need to be inspected. Since most of the Caltrans bridges in the State have been studied for retrofit and some have been retrofitted, the ARS values used in design of various elements in each bridge are known. For recorded earthquake shaking, when Sa (T) is greater than ARS(T)/Z, then bridge inspection is warranted.

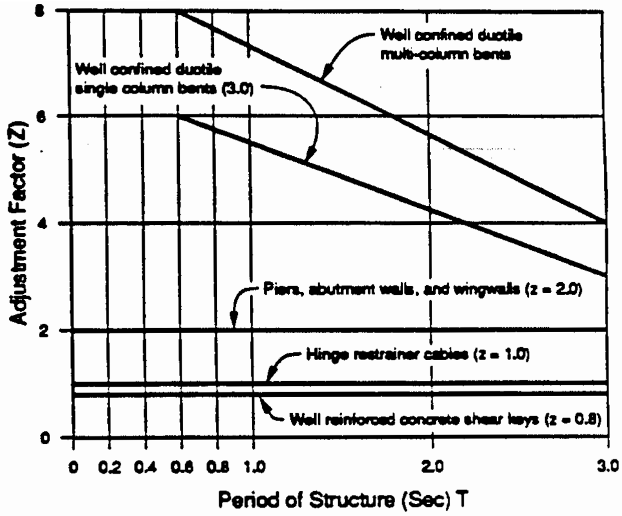

Figure 12. Factor, Z, for adjustment of seismic forces from the ARS curves, used is seismic designs of bridges (Caltrans, 1990).

Another screening criteria may be based on the displacements estimated from the recorded data. Dynamic models of these structures can tabulate the threshold displacements for a particular member prior to an event. This list of threshold deflections can be quickly compared with the near-real-time data recorded from these structures. These fragility lists can be developed for all the toll bridges and for important interchange bridges in the large urban areas. After only a few minutes of review the inspection efforts can be coordinated to concentrate on the areas of greatest concern. This is especially valuable for the large toll bridges which in some cases are many miles long.

It is extremely important to obtain the relative deflection of the large piers of the major toll bridges from the data right after an event. The piers with the most worrisome deflections will be assigned to the first inspection team. A large amount of analytical efforts will need to be put into these threshold lists because the capacity of shorter piers can be vastly different from the capacity of taller piers. The sooner a structure can be opened to the traffic the sooner emergency vehicles can utilize the route. A threshold-exceeded warning system can be set up in the toll plaza to give early bridge closure information to the toll captains after a large earthquake.

SUMMARY

The California Department of Transportation and the Department of Conservation continue to instrument bridges for strong motion to measure the ground motion and the response of the bridge structure to these motions. The strong-motion data recorded at these bridges provide valuable information for understanding the seismic response of the bridge and for improving seismic design and analysis procedures for bridges. In addition to these long-term objectives, the near-real-time recovery and processing of the recorded data is useful for post-earthquake evaluation of the bridges. The strong-motion data will be shared with other states and countries to improve seismic safety of bridge structures throughout the world. Bridge and soil-foundation-structure modeling techniques will be improved to reflect the actual measurements from the bridge structures. Continued efforts towards utilizing the near-real-time data for post-earthquake response and structural integrity assessments of the bridge must be ongoing and expanding.

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