HIGHLIGHTS OF STRONG-MOTION DATA FROM THE M6.0 SOUTH NAPA EARTHQUAKE OF AUGUST 24, 2014

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Abstract

The South Napa earthquake of August 24, 2014 caused the strongest shaking in the San Francisco Bay area since the 1989 Loma Prieta earthquake, 25 years earlier. Strong shaking occurred in the epicentral region, but low level shaking extended throughout the San Francisco Bay area. Over 400 strong motion records with peak accelerations above 0.5% g were recorded by the CISN seismic networks (BDSN, CGS/CSMIP, USGS/NCSN and USGS/NSMP) and these records are available at the CESMD website (www.strongmotioncenter.org) for view and download. Records with peak ground accelerations below 0.5% g are available for download at an associated FTP site.

Peak horizontal ground accelerations, velocities and spectral accelerations versus fault distance are compared with the ground motion predictions from Boore and Atkinson (2008; BA08). The comparisons show that the observed values are higher than would be predicted at distances less than about 20 km, while they generally drop off more rapidly with distance beyond that.

The last significant shaking in the Bay area was in the 1989 Loma Prieta earthquake. Many structures and sites have been instrumented since then, so this is the first set of significant data for many of these sites and structures. These structures include all of the major Caltrans toll bridges in the Bay area. For most of these bridges Caltrans also supported installation of geotechnical (downhole) arrays. The most striking new structure, the new Bay Bridge East Span, is not fully instrumented yet, though many channels were recorded. Another striking structure which recorded the first significant record is the recently instrumented concrete-core Rincon tower in San Francisco.

Strong-Motion Data from South Napa Earthquake

The Mw 6.0 South Napa earthquake occurred on August 24, 2014 at 03:20:44 PDT. The epicenter was at 38.216N and 122.312W, about 9 km SSW of Napa, California and about 82 km WSW of Sacramento, California. According to the USGS, the earthquake occurred near the well-known West Napa Fault. In the area of this earthquake, only the West Napa Fault is known to have displaced Holocene-age sediments. This earthquake was the most significant earthquake in Northern California since M6.9 Loma Prieta earthquake of October 17, 1989.

Strong-motion data were recorded from a total of over 445 CISN stations of the CGS Strong Motion Instrumentation Program (CSMIP), the USGS National Strong Motion Project (NSMP) and Northern California Seismic Network (NCSN), and the UCB Berkeley Digital Seismic Network (BDSN). The data also includes records obtained by the CA Dept. of Water Resources and P G & E. The stations are shown in the CESMD interactive map (Fig. 1) The strong motion stations include over 340 ground response stations, over 89 structures (buildings, bridges and other) and 14 geotechnical arrays. As of 6 October 2014, over 3000 channels (components) of strong-motion data are available for download through the Center for Engineering Strong Motion Data (CESMD) at www.strongmotioncenter.org. All of the ground-response data were used in the ShakeMap for the event. This note is focused on the engineering aspects of the strong motion data.

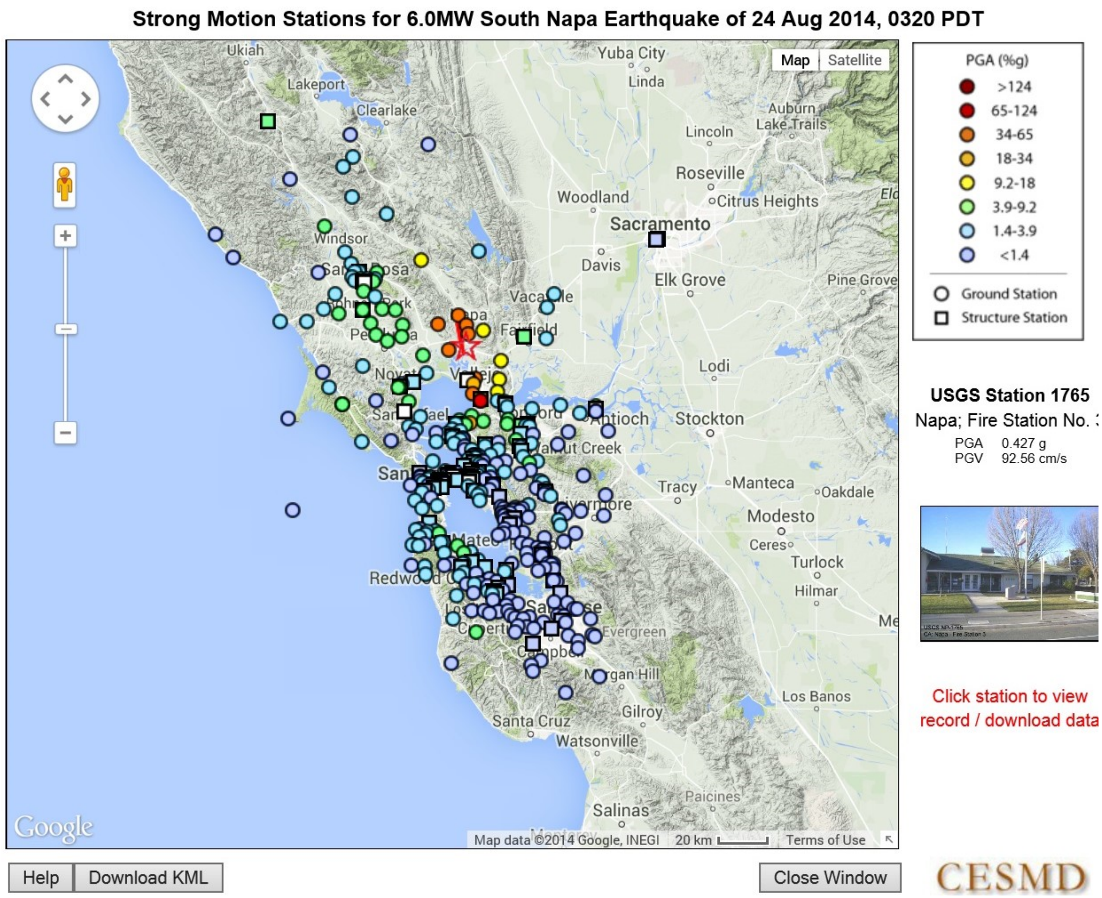

Figure 1. The interactive map at the CESMD website (www.strongmotioncenter.org) showing locations of strong-motion stations that recorded the South Napa earthquake.

The largest peak ground acceleration of 99%g was recorded by the surface instruments of the Crocket - Carquinez Br Geotechnical Array #1 (CGS 68206). The peak ground velocity at this station is 22 cm/s. A station on Main Street in downtown Napa (USGS N016), where the heaviest damage occurred, had a peak acceleration over 60% and a PGV of 47 cm/s. Napa Fire Station 3 (USGS 1765) in the northern part of Napa had the largest PGV, at 93 cm/s, with a PGA of 43%g. The duration of strong shaking was generally 10 to 15 seconds or less.

Near-Fault Ground Motions

Recorded ground accelerations in the Napa area and in the city of Vallejo are generally very strong with peak ground accelerations larger than 0.3 g. Many of the buildings in the Napa and Vallejo areas suffered damage to the chimneys and URM walls or facades. The recorded ground accelerations from five stations in the Napa area and three stations in Vallejo, in the east-west direction, are plotted on the CESMD interactive map in Figure 2. Perhaps due to the fact that the fault rupturing was from south to north (Dreger, 2014), the records in Vallejo tend to have two distinct arrivals separated by about 1.8 seconds. Although some of these records have relatively large peak accelerations, the peak velocities were not large because the peak accelerations were the results of high frequency motions.

Ground velocities integrated from recorded accelerations in the east-west direction are plotted on the CESMD interactive map in Figure 3. It is clear that the peak ground velocities in the Vallejo area are smaller than those in the Napa area. Some distinctly large velocity pulses are seen in the records in the Napa area. The largest peak ground velocity of 93 cm/s was recorded at NAPA Fire Station 3. It appears that the source mechanism plays a very significant role in generating large velocity pulses in the near field.

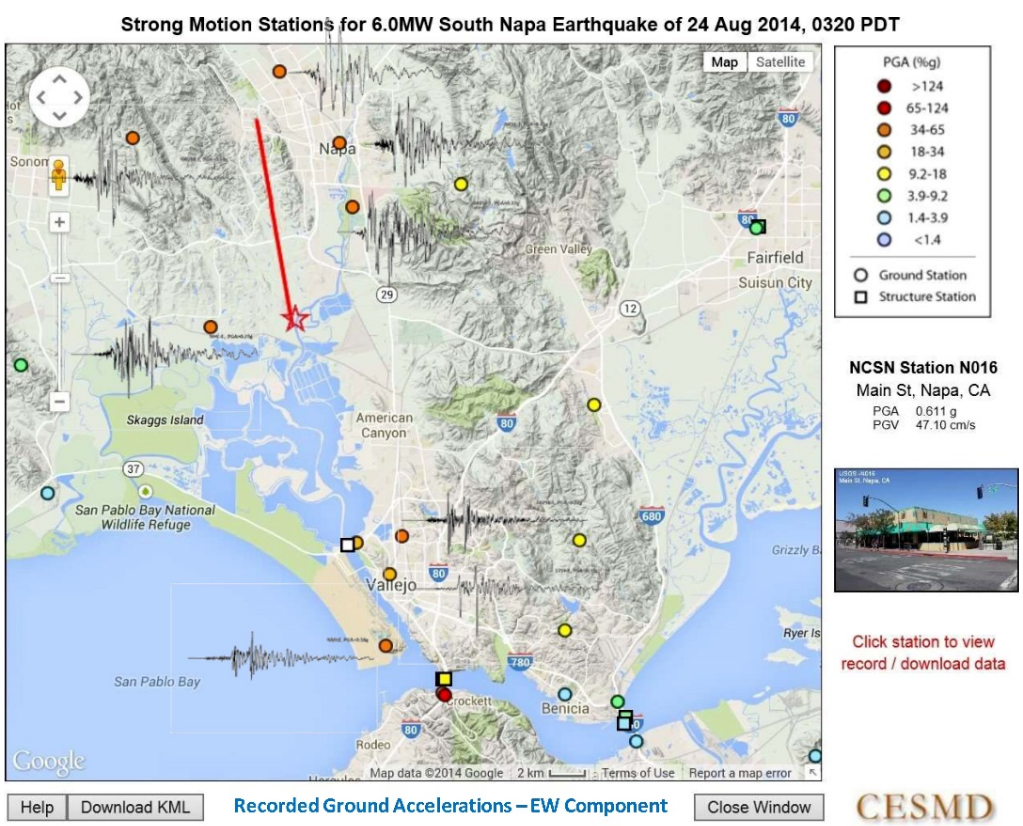

Figure 2. Recorded ground accelerations, EW component, in the Napa and Vallejo areas. Records of 20 seconds are plotted, with the same scale, on the CESMD interactive map.

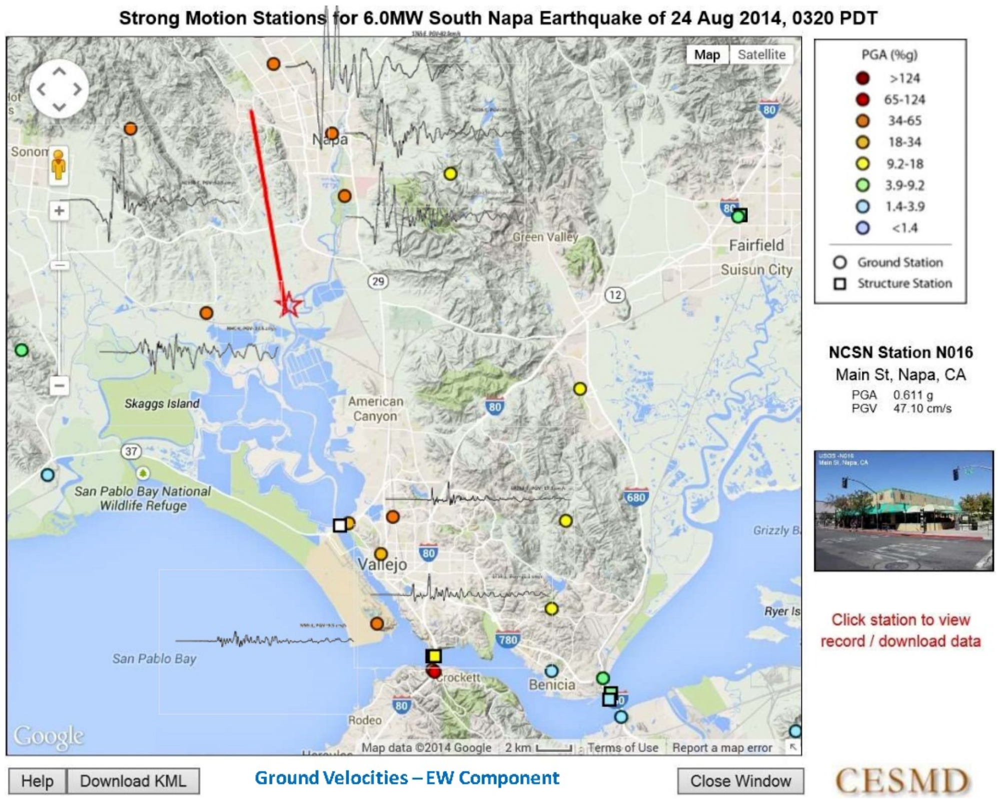

Figure 3. Ground velocities, EW component, in the Napa and Vallejo areas on the same base map as Figure2. Records of 20 seconds length are plotted, with the same scale, on the CESMD interactive map.

Peak Ground Motion Analyses

Peak Ground Acceleration

The Napa earthquake had high close-in accelerations that decayed relatively rapidly with distance. Figure 4 shows the geometric mean of the peak horizontal ground accelerations vs. the Rjb distance, the closest distance of a station to the projection of the fault model on the ground surface. The fault model was developed by Dreger (2014) at University of California, Berkeley and modified by Boatwright (personal communication) of the USGS.

The observed PGA values are compared with the ground motion predictions from Boore and Atkinson (2008; BA08) assuming a Vs30 of 760 m/s and strike-slip faulting. In general, the observed acceleration values are higher than the values that would be predicted at distances less than about 20 km, but many are within one standard deviation. Beyond that, the observed values generally drop off more rapidly than would be predicted, with many stations more than one standard deviation low.

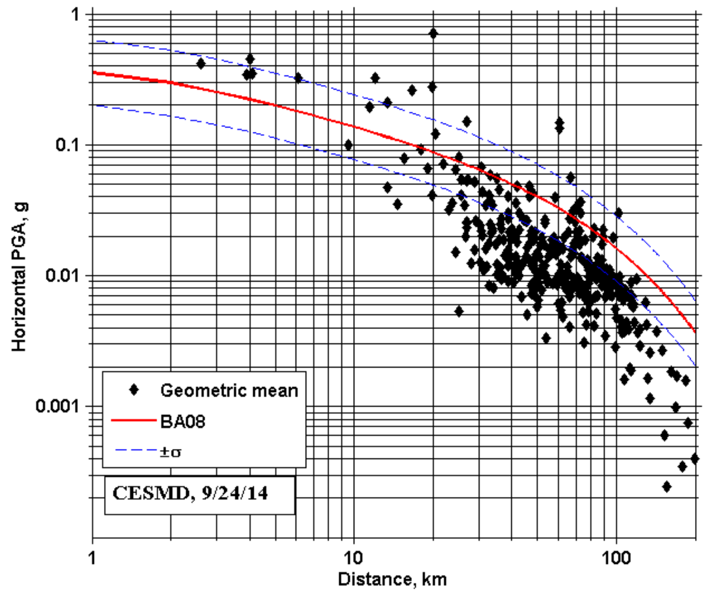

Figure 4. Peak horizontal ground acceleration (geometric mean) versus distance (Rjb), compared to the BA08 model of Boore and Atkinson (2008).

Peak Ground Velocity

It is also useful to compare the peak horizontal ground velocity vs. Rjb distance with the ground motion predictions of BA08, again assuming a Vs30 of 760 m/s and strike-slip faulting (Figure 5). The observed ground velocities are high close-in, but drop off beyond that. In general, the fit of the velocity data is better than that of the acceleration data.

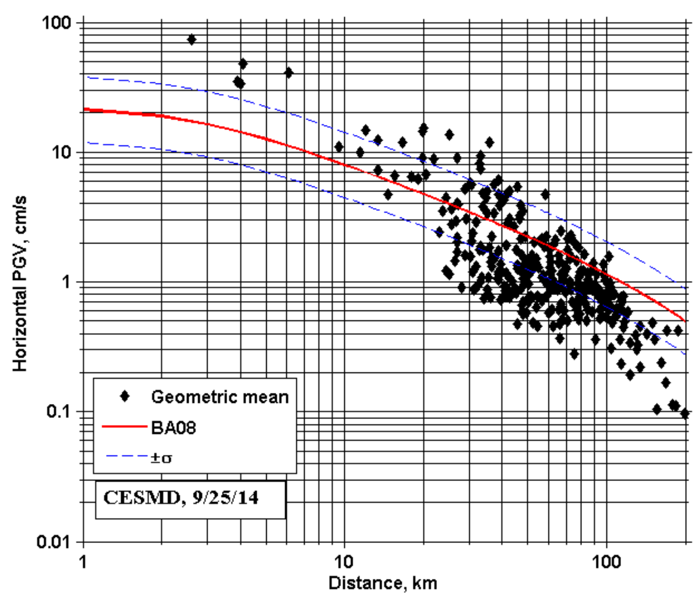

Figure 5. Peak horizontal ground velocity (geometric mean) vs. Rjb distance, compared to the BA08 model.

Spectral Acceleration

Spectral acceleration (geometric mean) values calculated at the three periods of 0.3, 1.0 and 3.0 seconds are plotted versus fault distance (Rjb) in Figure 6. Like the acceleration and the velocity versus distance plots, the spectral accelerations at the three periods also show higher observed values in the near field, and dropping off more with distance in the far field, compared to the spectral acceleration prediction of BA08.

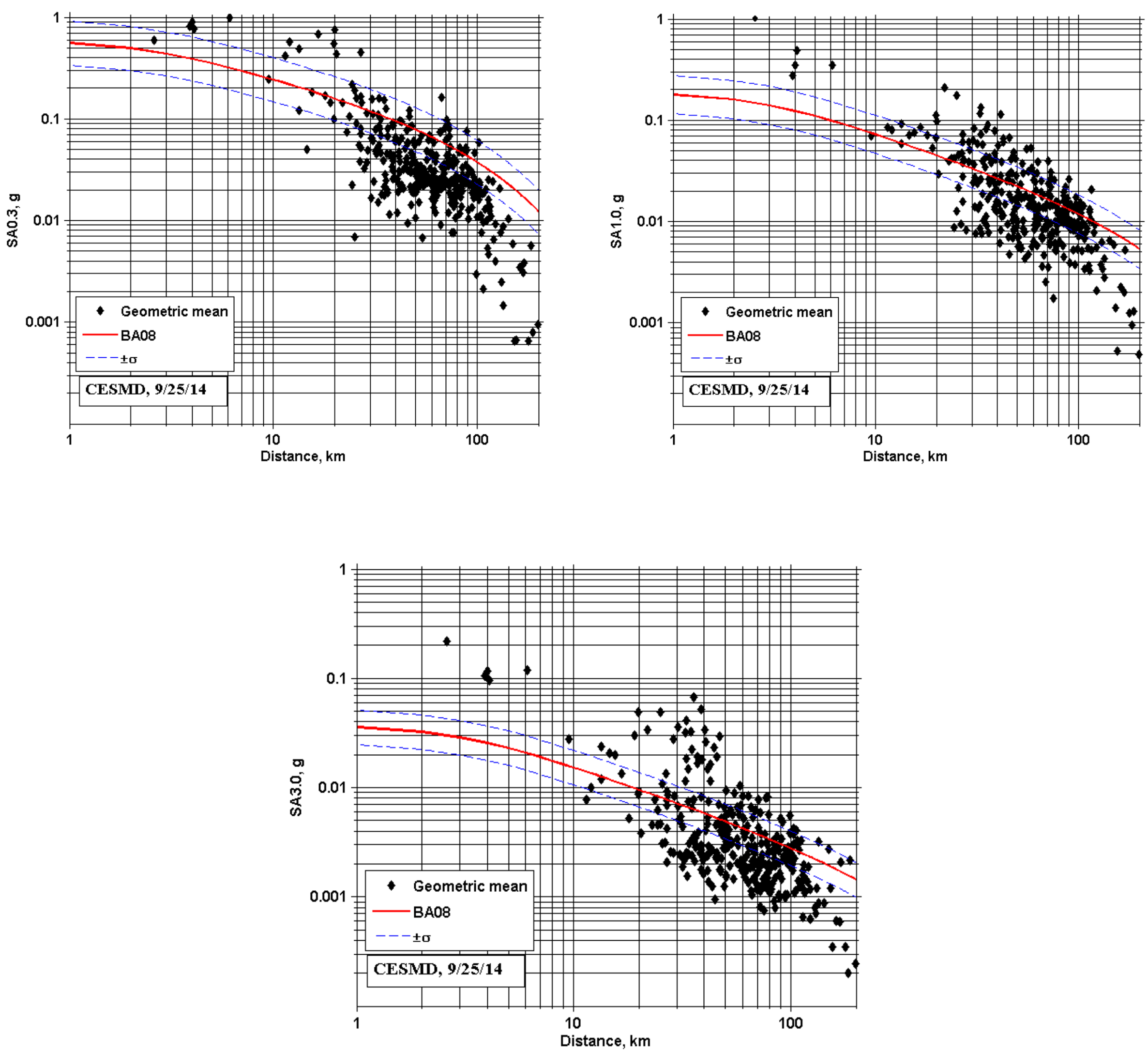

Figure 6. Spectral accelerations versus distance, compared to the BA08 model, for periods of 0.3 sec (upper left), 1.0 sec (upper right), and 3.0 sec (lower)

Strong-Motion Data from Geotechnical Arrays

Strong-motion data from the South Napa earthquake was recorded by14 geotechnical arrays and the data are available for download. The largest peak ground acceleration of 99%g was recorded by the surface instruments of the Caltrans-supported Crocket – Carquinez Br Geotech Array #1 (CGS 68206) near Crocket. The peak ground velocity at this station was 22 cm/s, not unusually high. It is striking that the Crocket – Carquinez Br Geotech Array #2, about 0.2 km from Array #1, recorded peak ground acceleration of 44%g on the ground surface instruments. The significant difference in ground motion at the two arrays could be due to site effects, path effects, structural response impacts. Studies to understand the motions are beginning. Figures 7 and 8 show strong motion acceleration plots at the two geotechnical arrays.

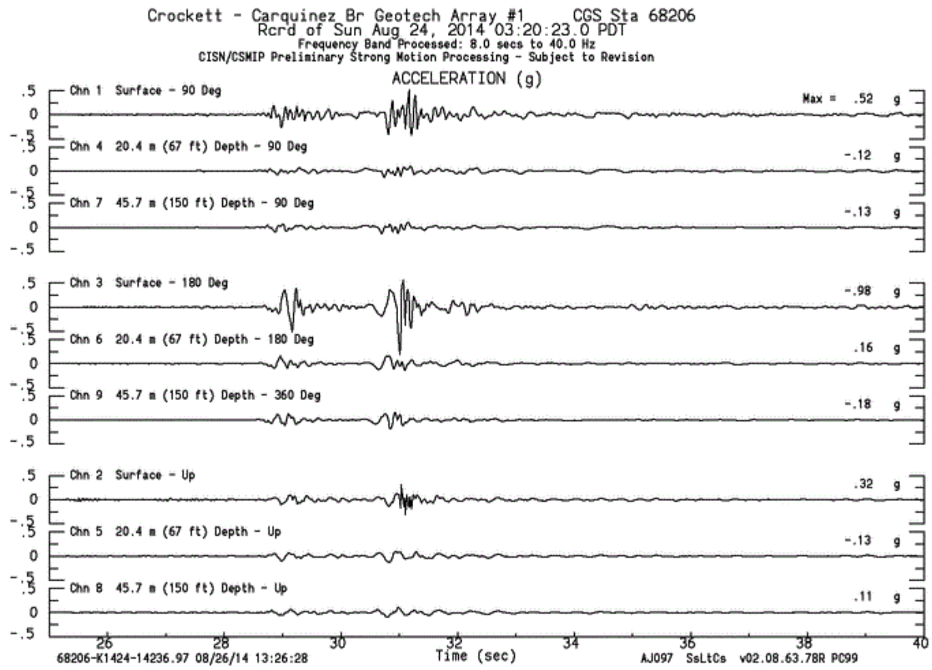

Figure 7. Strong-motion record of Napa earthquake at Crocket – Carquinez Br Geotech Array #1.

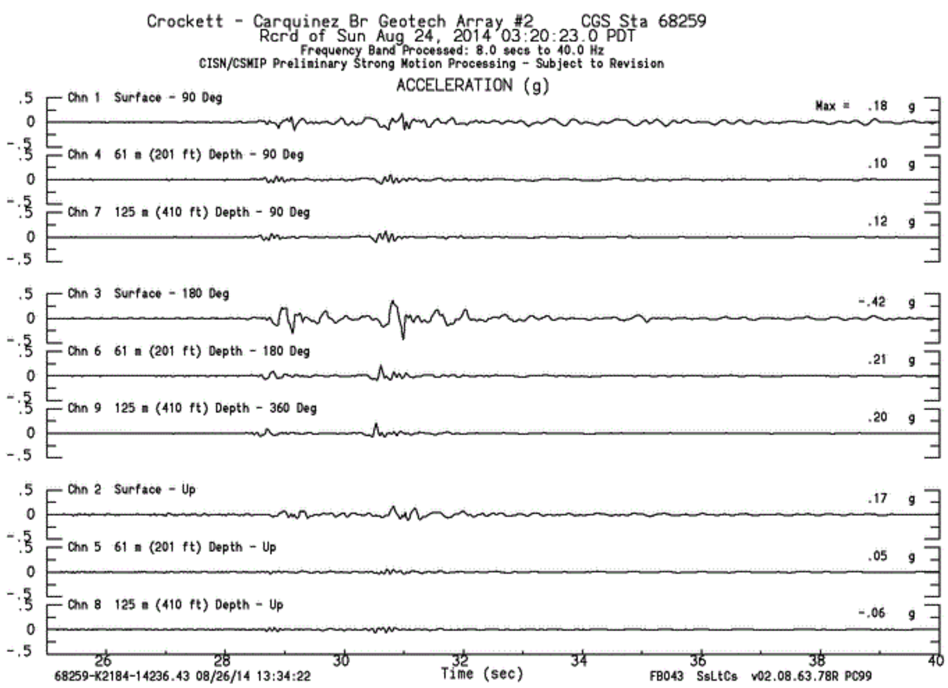

Figure 8. Strong-motion record of Napa earthquake at Crocket – Carquinez Br Geotech Array #2.

In addition to the South Napa earthquake mainshock, two aftershockes, an M3.6 on August 24 and an M3.9 on August 26, were recorded at the Geotechnical Arrays #1 and #2. Both aftershock epicenters were north-west of the geotechnical arrays, the first one at about 23 km distance and the second one about 16 km. Like in the mainshock, the observed ground motions from both aftershocks were larger at Geotechnical Array #1 ground surface, compared to those at the Geotechnical Array #2. The ratio of maximum ground acceleration at the Geotechnical Array #1 to the maximum at the Geotechnical Array #2 is 2.2 for the mainshock, and 1.8 and 1.7 for the two aftershocks. These observations suggest that the significant differences of peak ground accelerations at the two geotechnical arrays are probably not due to the source effects, since the mainshock and both aftershocks show the same high amplitude ground motion at the Geotechnical Array #1. Full understanding will await the results of studies now beginning.

Strong-Motion Data from Structures

Strong-motion records were obtained from a total of 89 structures during the South Napa earthquake. These structures include 64 buildings, 17 bridges, 3 tunnels/underground tubes, 4 wharves and 1 dam. Among 64 buildings, 11 are hospital buildings. Ten of the 17 bridges are toll bridge structures. The closest structure was the Hwy37/Napa River Bridge in Vallejo, 11 km from the epicenter. The peak ground shaking near the bridge is about 0.2g and the largest acceleration in the bridge response records is 0.66g. The closest building is the 3-story hospital in Fairfield, 24 km from the epicenter. Peak ground acceleration at the hospital is 0.04g, while the peak response of this steel structure was 0.17g. Many of the buildings in the San Francisco and Oakland areas experienced low-level ground shaking of only about 0.02g. However, records were obtained from buildings located in Sacramento and San Jose, which are about 82 and 105 km from the epicenter, respectively.

The most significant and important structural response records were obtained from Carquinez suspension bridge in Vallejo. This bridge is located about 19 km from the epicenter. The peak ground acceleration at the north abutment is about 0.08g and the suspension bridge recorded 0.79g on the main cable. The older bridge east of the suspension bridge, a steel truss structure, also experienced strong shaking and recorded high level of structural response. Both the north bound (concrete box girders) and the south bound (steel truss girders) bridges connecting Benicia and Martinez recorded structural response higher than 0.10g. The Golden Gate Bridge, 46 km from the epicenter, experienced larger structural response during the South Napa earthquake than in six previous earthquakes.

San Francisco – 62-story Residential Building

The first earthquake records were obtained from the 62-story residential building in San Francisco. The building is a tall concrete core shear wall structure. The instrumentation with 72 sensors was completed in 2012 in cooperation with USGS (Huang et al, 2012). Celebi et al. (2012 and 2013) analyzed the ambient motions due to wind to obtain the modal frequencies and mode shapes. Celebi (personal communication, 2014) does not see much difference in modal frequencies in the low-level seismic motion compared to the wind records.

Carquinez Suspension Bridge

The Carquinez suspension bridge was built and opened in 2003 to replace the original 1927 span. It is a cable suspension structure and is one mile long. The cable suspension bridge uses an isotropic steel box girder and has two concrete towers. The approach structure and the off ramp are concrete box girders. Both the main suspension and the off ramp structures were instrumented as part of the construction project. The suspension structure is extensively instrumented with 76 sensors while the approach structure and the off ramp were instrumented with 27 sensors (Huang et al., 2013). Sensors are placed along the height of both towers and in both anchorages. Sensors are planned to be installed on the pile cap and the pile tips at both towers, but they have not yet been installed. The suspended roadway is instrumented at eight locations along its length and typically accelerometers are placed inside the steel box girder. The box girder is continuous with shear keys at the towers. The box girder is allowed to move longitudinally and connected with viscous dampers at the towers. Sensors were also installed on the suspension cables at two locations to measure the transverse motions of the main cable. A geotechnical array (CGS 68259, Array #2) with sensors on the ground surface and at two depths was installed near the south anchorage of the bridge.

Before the South Napa earthquake, ambient motion data were recorded from the suspension bridge and were analyzed by system identifications to obtain the modal frequencies and mode shapes (Conte et al., 2008; Betti et al., 2008). The data from the South Napa earthquake is the first set of data obtained from the bridge during a seismic event. Although the design ground motions for the bridge are much higher than what the bridge experienced in the South Napa earthquake, the data provide excellent opportunities to calibrate the existing computer models and test various health monitoring methodologies.

Figure 9 shows 150 seconds of the recorded accelerations in the transverse direction at various heights of Tower T2. Peak accelerations were 0.159, 0.239, 0.164, and 0.126 g at the pile cap, lower strut, El. 80 m and the top, respectively. These peaks occurred during the first 20 seconds of ground shaking. The largest peak occurred at the lower strut, which supports the deck box girder. Close examination of the records shows that the tower was vibrating at a higher mode with a period of about 1 second. In this mode, the tower top was moving 180-degree out of phase with the lower strut. For the same locations, the corresponding displacements are shown in Figure 10. It is clear that after the ground shaking ceased, the whole bridge structure was in free vibration. The tower was dominated by the mode with a longer period (about 2.6 second), in which the tower displacements along its height are in phase. One can also compute relative displacements between these locations. For example, the maximum movement of the tower top relative to the pile cap is about 6 cm. Similar analysis can be performed for the motions of Tower T2 in the longitudinal direction, and Tower T3 in both directions.

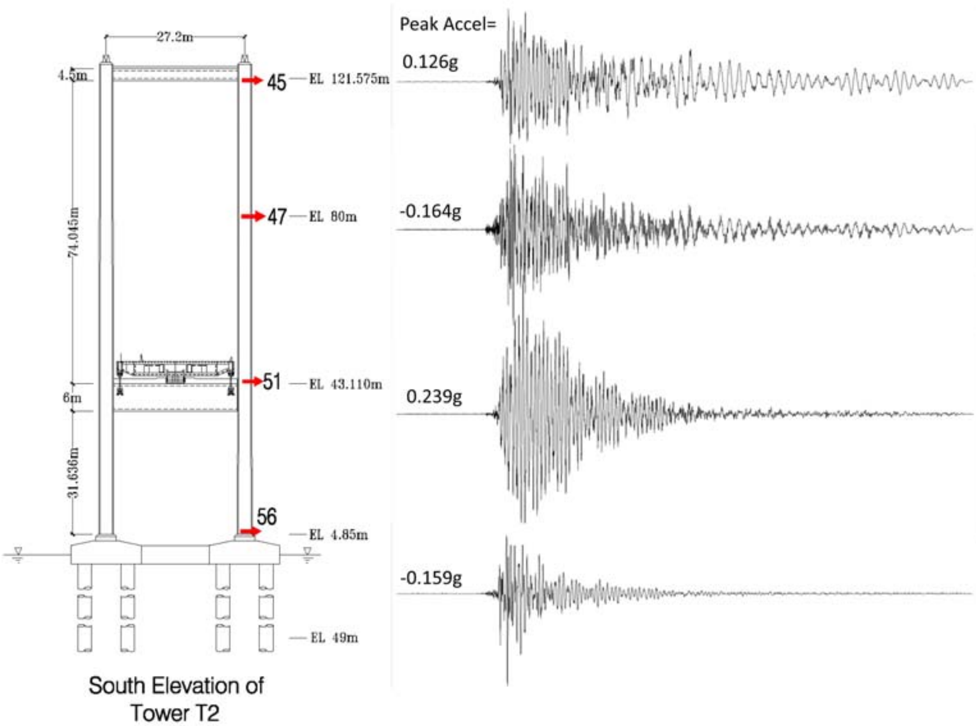

Figure 9. Recorded accelerations at Tower T2 of the Carquinez suspension bridge, in the transverse direction. Records of 150 seconds are plotted with the same amplitude scale.

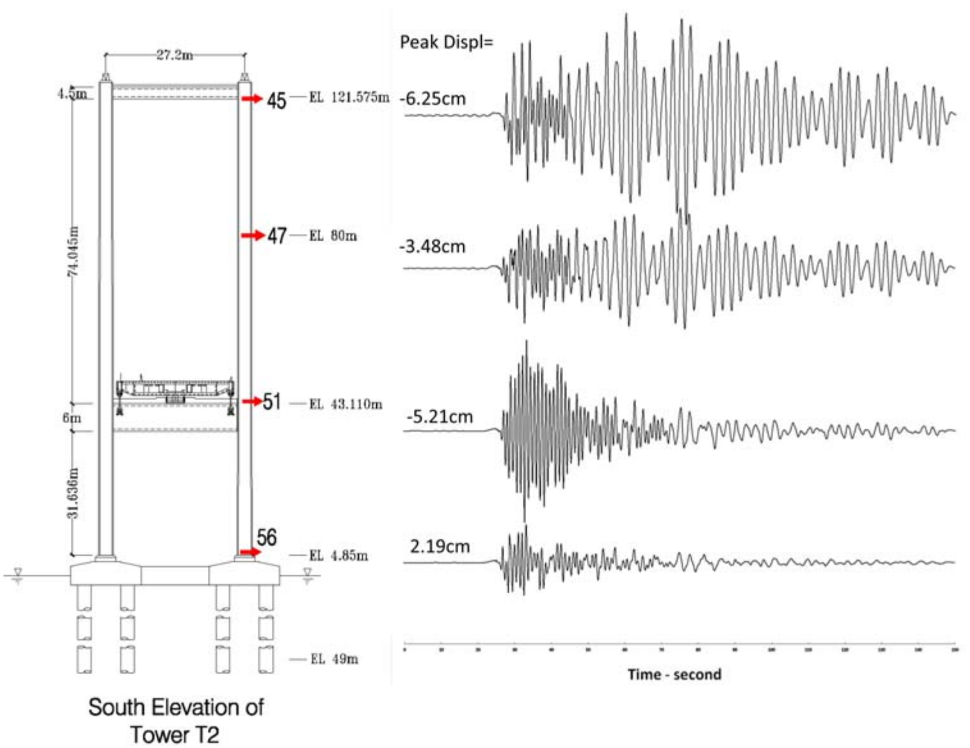

Figure 10. Displacements at Tower T2 of the Carquinez suspension bridge, in the transverse direction. Records of 150 seconds are plotted with the same amplitude scale.

Figure 11 shows 150 seconds of the displacements in the transverse direction along the deck box girder. For comparisons, the displacement at Abut A4 is also shown, which is much smaller than any points of the deck. The deck movement is constrained at both towers. It is interesting to observe that peak displacements occurred during the first 20 seconds for all locations and the amplitudes were not much different. The motions are dominated by a mode with a period of 0.5 second. However, in the later part of the record, the movements are larger in the center span than the side spans, and have a period of about 5.5 seconds, which is the period of the first mode (mainly transverse movement). Similar analysis of the records can be performed for the vertical and torsional motions of the box girder. Torsional response of the deck box girder seems to be dominant in the record.

More sophisticated system identifications can be performed on the records from many locations on the bridge. The modal frequencies and mode shapes can be compared with those derived from ambient vibration data to see how the bridge response parameters change from the baseline model parameters during the South Napa earthquake. These parameters can also be used to calibrate the existing finite element models for the bridge.

CSMIP Network Performance

The CSMIP program has a long-standing performance goal that 95% of the installed instrumentation should operate correctly in a given earthquake. Overall, the network performance was slightly less than that in this earthquake. However, that goal was reached and exceeded for conventional ground response stations, for buildings, and for hospital stations, each category had correct operation of over 98%. However, bridges and related stations were significantly less, near 85%. It was necessary to suspend maintenance late last year because of Caltrans funding shortfalls. Nonetheless, many good records were obtained, and the first records from many Caltrans-supported stations, because of the large number of new bridge installations that have come on in the last 5-10 years.

New Developments – New CSMIP Installations and New Types of Sensors

In-Pile Instrumentation

It is customary to locate strong motion sensors on the superstructure of bridges and other structures. However, it is desirable to know the motions input to the structure, through the piles under the structure. Installation of accelerometers in piles is significantly more difficult, technically, than other types of instrumentation. Downhole instrumentation in geotechnical arrays are similar, but the typical plastic (PVC) casing, and the controlled environment, make the installation easier. In-pile strong motion instrumentation requires steel casings, and in addition the construction environment means the casing often ends up with debris at the bottom, making the installation difficult. The first records obtained from sensors with known instrument orientation in downhole steel piles were recorded in this earthquake at the Benicia Bridge. The steel of the casing and the rebars in a pile make orientation via magnetic compass not possible, and other means had to be developed. CSMIP has several bridges for which in-pile instrumentation will be done as soon as an economical method to solve the debris problem is developed.

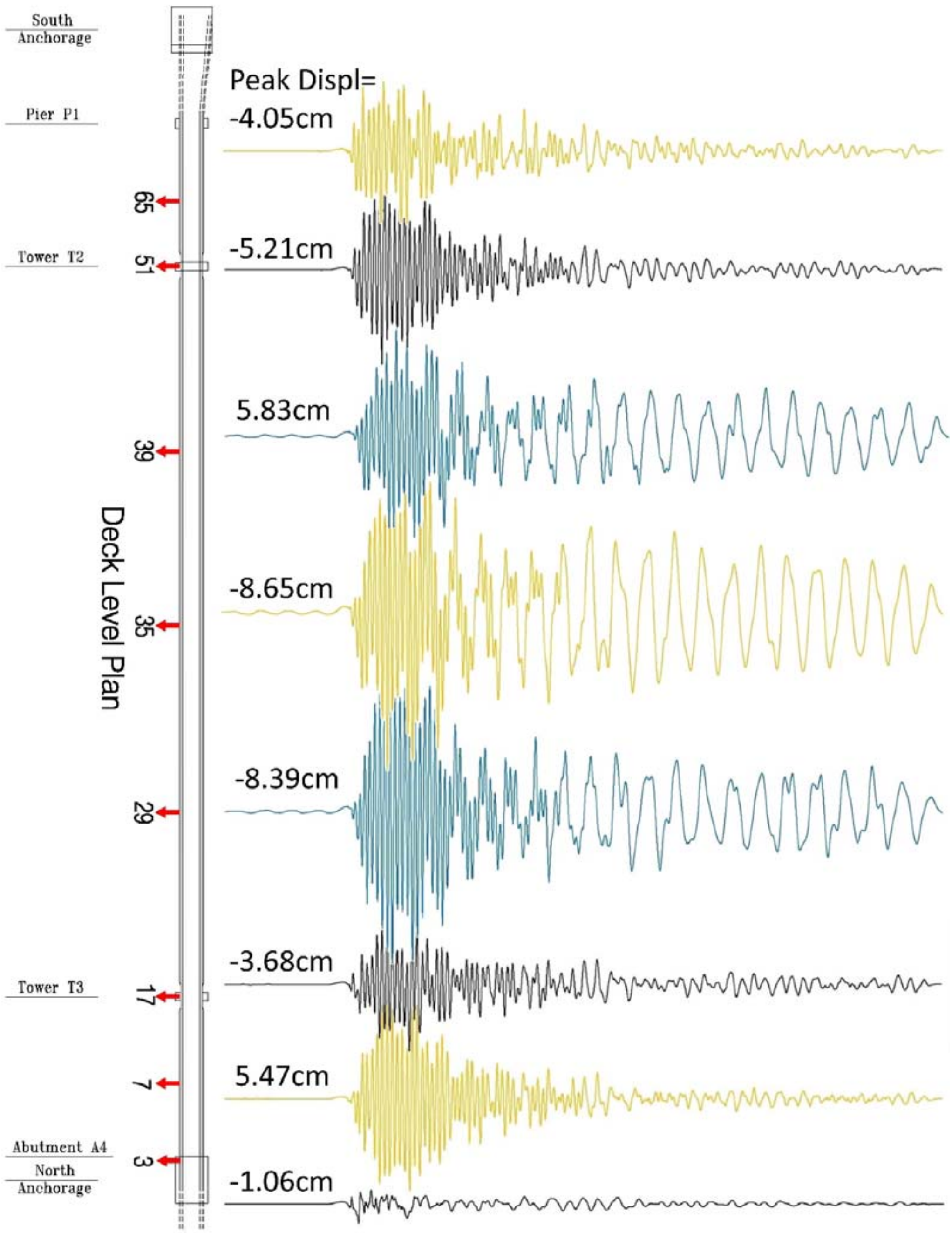

Figure 11. Displacements along the length of the deck box girder of the Carquinez suspension bridge, in the transverse direction. Records of 150 seconds are plotted with the same amplitude scale.

Strong Motion Instrumentation of Wharf Structures

The San Francisco Bay Conservation and Development Commission (SFBCDC) has begun requiring facilities in near-shore areas which are being built or modified to incorporate strong motion instrumentation. Two recently completed structures with strong motion instrumentation include the Brannan Street Wharf in San Francisco (CGS 58559) and Redwood City's new shipping wharf (CGS 58566). The Brannan Street wharf sensor layout (Fig. 12) includes in-pile instrumentation, and Fig. 13 shows the data recorded at the pile tip, at 85 ft. depth. The wharf also includes instruments on the sea wall, as separate from the deck structure.

The Redwood City shipping wharf is the first case where SMIP has installed a tilt sensor on the structure, as reflected in the sensor layout in Fig. 14. (The new East Span of the Bay Bridge will also be instrumented with tilt sensors in the tower as construction is finished later this year.) Fig. 15 shows the tilt signal recorded, transverse to the long dimension of the structure. The data is also interesting as it shows apparent rotational motion of the wharf, that is, different transverse motion at the South end compared to the North.

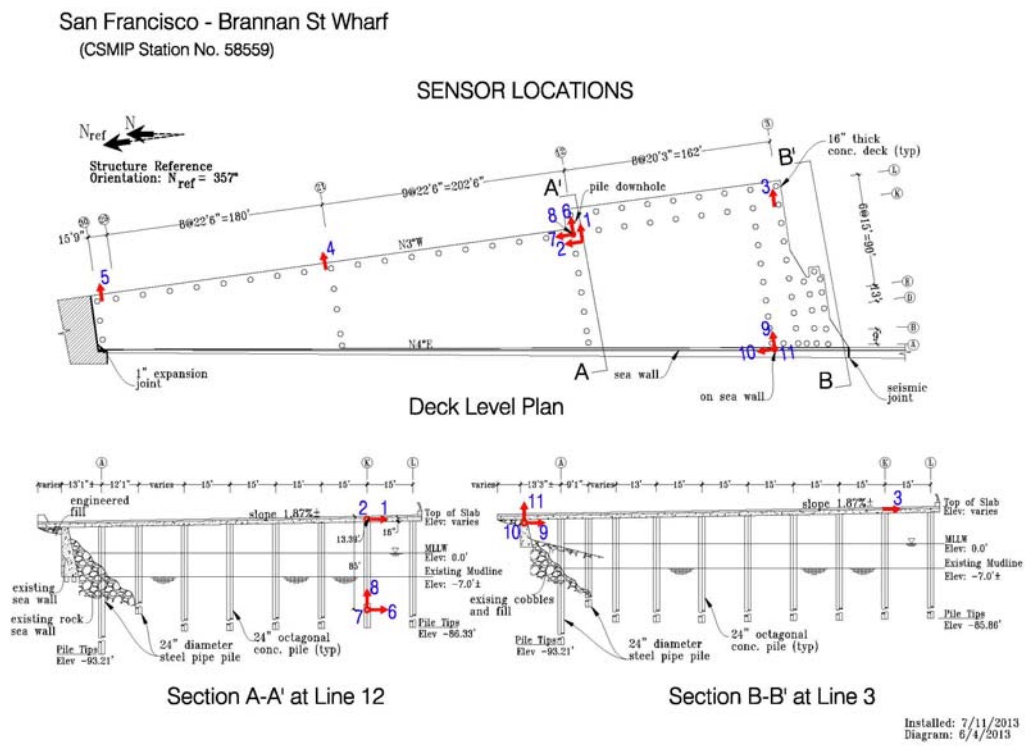

Fig. 12. Locations of sensors on the recently instrumented Brannan Street Wharf in San Francisco (CGS 58559). The instrumentation includes sensors in the pile-tip (sensors 6,7,8) and on the sea wall (sensors 9,10,11).

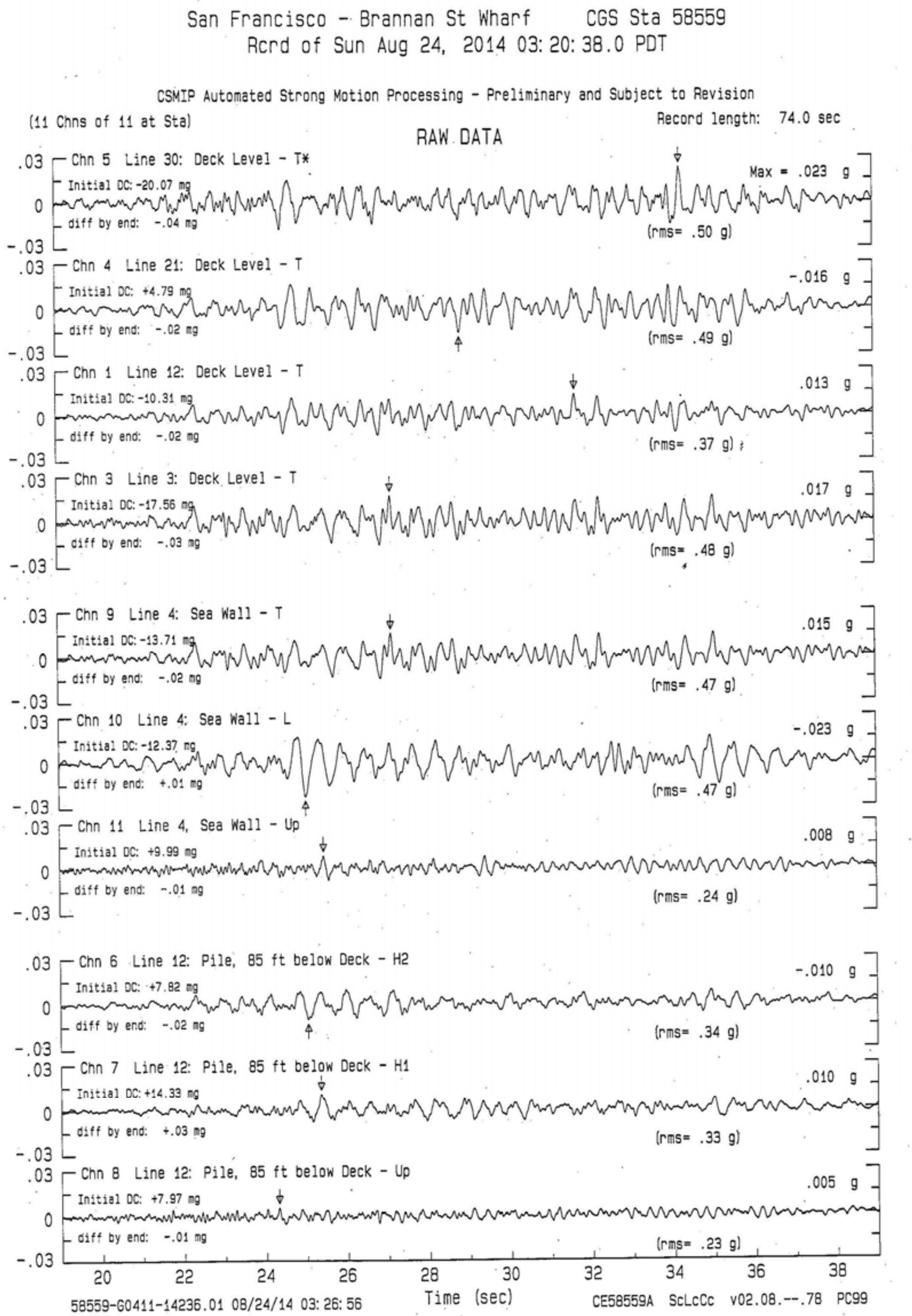

Fig. 13. Recorded accelerations at the Brannan Street Wharf during the South Napa earthquake, along the deck level (upper), sea wall (center) and at the pile tip (lower).

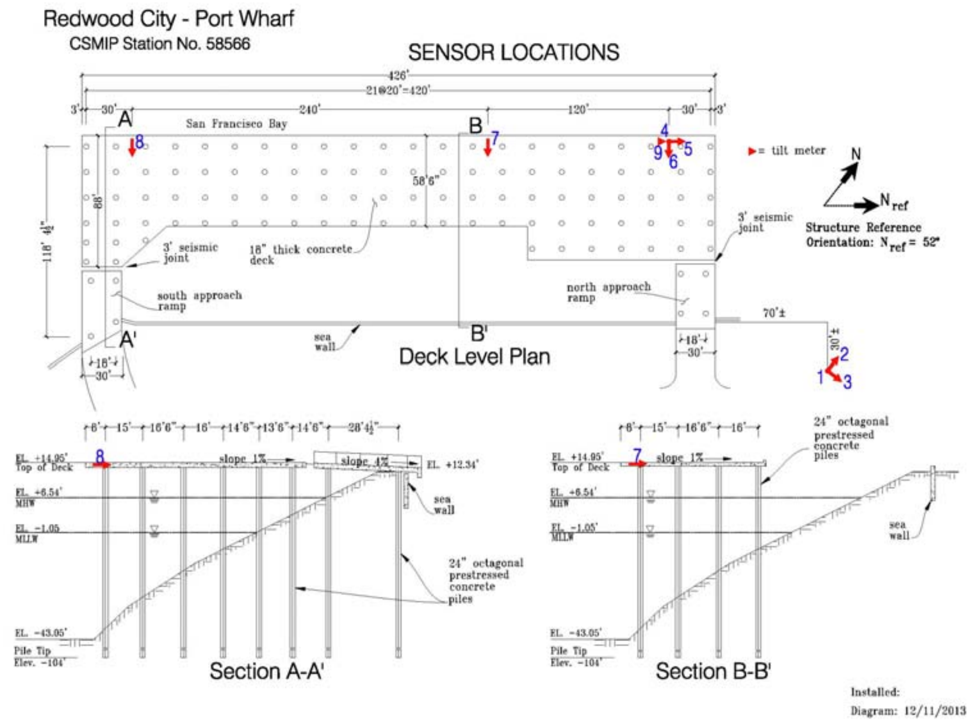

Fig. 14. Locations of sensors on the recently instrumented Redwood City Port Wharf (CGS 58566). The instrumentation includes three free field sensors, three transverse sensors along the length of the wharf (6,7,8) and a tilt sensor (9), sensitive to tilt around the longitudinal axis of the wharf.

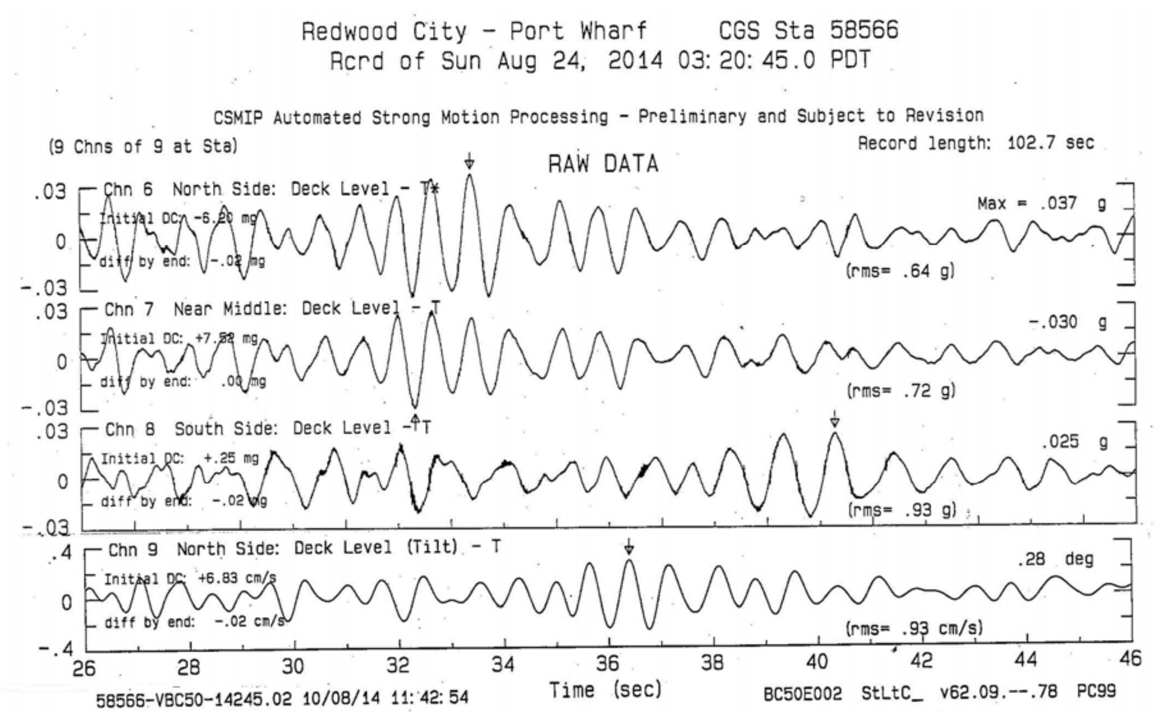

Fig 15. Recorded motions at the Redwood City Port Wharf during the South Napa earthquake, transverse accelerations (upper), and tilt (lower).

Direct Measurement of Relative Displacement in Strong Motion

Accelerometers can provide very accurate measurement of accelerations. If displacement is desired, however, accuracy is generally lower because the acceleration signal must be integrated twice, a process in long period noise increases. It is possible to obtain the relative displacement between two points on a structure without the long period noise problem if relative displacement sensors are used. CSMIP has been installing relative displacement sensors, between the superstructure of an isolated building and the base, for example, for many years. The first relative displacement sensors were installed as part of the Golden Bridge instrumentation in the mid-1990s. Despite the relatively large number of such cases, the first significant relative displacement record was not obtained until the 2014 Napa earthquake. Fig 16 shows the location of the measurement, made between a tower and the deck structure of the western suspension span of the Bay Bridge. Fig. 17 shows a plot of the relative displacement between the deck and Tower 3 of the west span of the Bay Bridge. The damper was installed as part of Caltran's retrofit of the West Span, and the sensor was recently added to the Caltrans-supported instrumentation system to measure the motion across the damper.

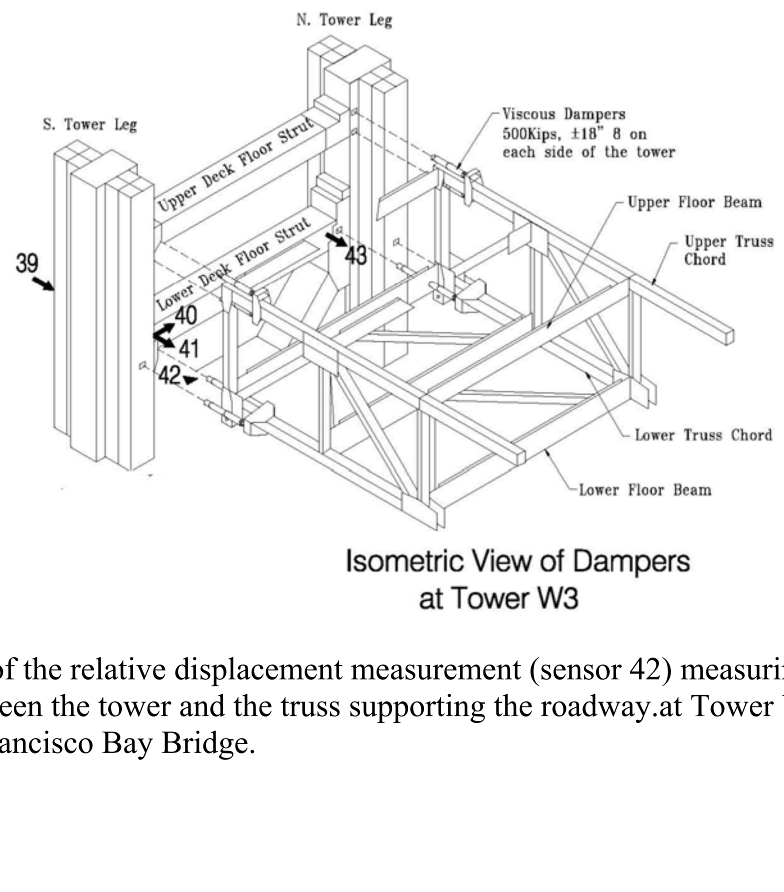

Fig 16. Location of the relative displacement measurement (sensor 42) measuring the relative displacement between the tower and the truss supporting the roadway.at Tower W3 of the West Span of the San Francisco Bay Bridge.

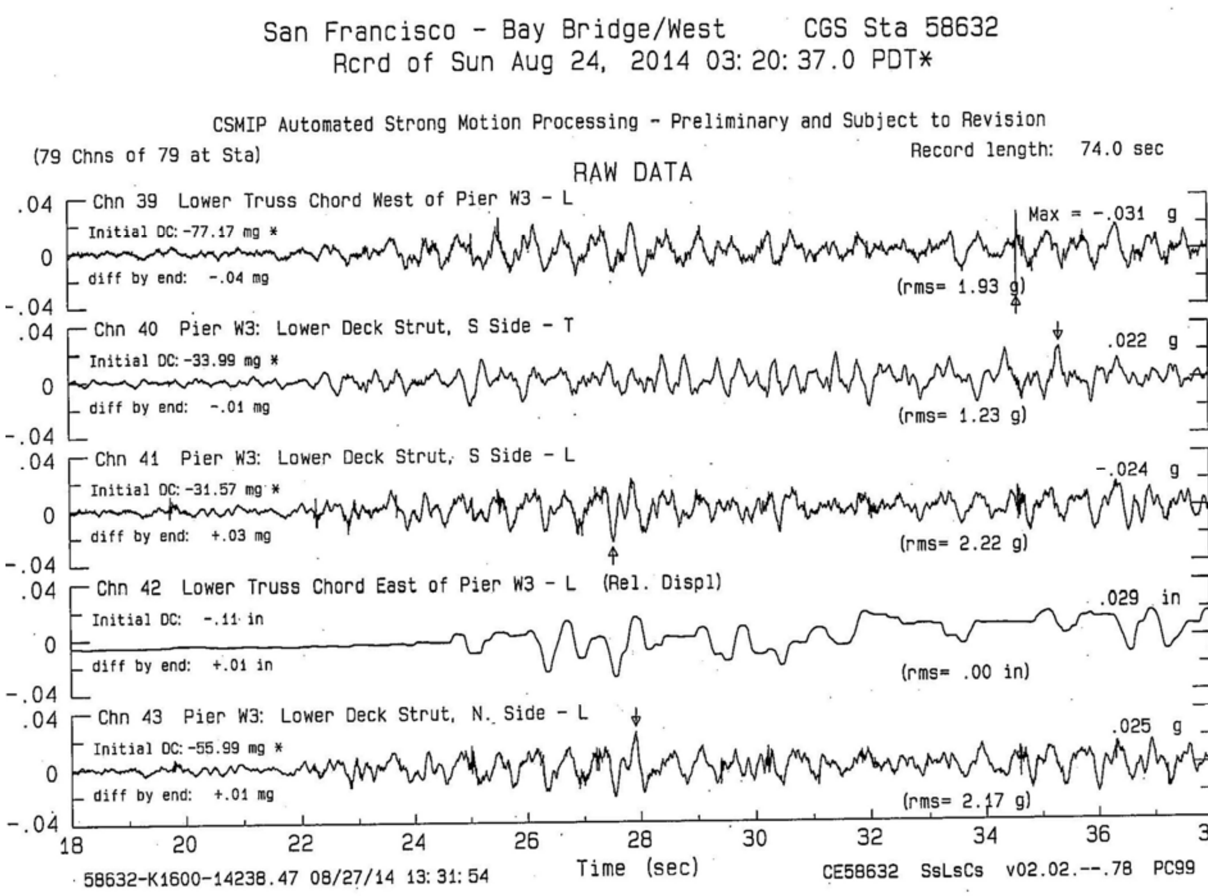

Fig 17. Relative displacement (chan 42; others are nearby accelerometers) between the tower and the roadway truss at Tower W3 of the West Span of the San Francisco Bay Bridge during the South Napa earthquake.

Cable Sensors

Recently instrumented suspension bridges have included sensors on the suspension cables themselves, as part of the Caltrans-supported instrumentation system. The Carquinez Bridge was the first bridge in which the instrumentation included accelerometers on the main cables at two locations. The nearly competed instrumentation of the new SFOBB East span now being completed also includes cable instrumentation, with triaxial sensors.

Petroleum Wharves

In recent years, the California State Lands Commission and the SFBCDC have encouraged strong motion instrumentation of petroleum wharf facilities, and SMIP has worked with the wharf owners to accomplish the instrumentation. The first outcome is an oil wharf near Richmond, which was instrumented in 2003, and good data was recorded during the Napa earthquake. The motion was low level, about 3% g. Oil wharves represent critical lifeline structures, and the measurement of their response during strong shaking is important. However, they also can present particularly difficult installation challenges, because of the explosion-proof conditions that must be adhered to. Instrumentation is underway on two additional wharves in the Bay area, to be completed in the next several years.

Data Access

All of the data discussed here is available through the Center for Engineering Strong Motion Data (CESMD), a joint effort of the CGS California Strong Motion Instrumentation Program and the USGS National Strong Motion Project. The files for all records are available at www.strongmotioncenter.org, having gone through processing and error checking. Both the processed data and the raw data are available and can be downloaded. Users are encouraged to revisit this web site for updated information and data. The ground response data is also available from the CESMD Virtual Data Center at http://strongmotioncenter.org/vdc.

Acknowledgements

Station siting permission from property owners in the Bay area is acknowledged and appreciated. Careful field installation and maintenance work by field technical staff of both CGS and USGS was critical to successfully recording the strong motion during this earthquake, and it is also acknowledged and appreciated. Lijam Hagos's contribution in preparing ground motion figures is appreciated. Many of the records recovered in this earthquake would not be possible without the support of Caltrans, CalOES, OSHPD, DWR, Golden Gate Bridge, Livermore National Laboratory and BSEE.

References

Boore, D. M., and G. M. Atkinson (2008), Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-Damped PSA at spectral periods between 0.01s and 10.0s, *Earthquake Spectra*, *24*(1), 99-138.

CESMD, Center for Engineering Strong Motion Data Website, South Napa Earthquake of 24 Aug 2014, last visited on October 7, 2014. (www.strongmotioncenter.org)

Celebi, M., Huang, M., Shakal, A., Hooper, J. and Klemencic, R., Ambient Response of a Unique Performance-based Design Tall Building with Dynamic Response Modification Features, *Journal of the Structural Design of Tall and Special Buildings*, Volume 22, Issue 10, July 2013, Pages: 816–829

Celebi, M., Huang, M., Shakal, A., Hooper, J. and Klemencic, R. Ambient Response of a Unique Performance-based Design Building with Dynamic Response Modification Features, *Proceedings of SMIP12 Seminar on Utilization of Strong-Motion Data*, October 2, 2012, pp. 97 - 110.

Conte, J.P., He, X., Moaveni, B., Masri, S.F., Caffrey, J.P., Wahbeh, M. Tasbihgoo, F., Whang, D.H and Elgamal, A. (2008). "Dynamic Testing of Alfred Zampa Memorial Bridge." *Journal of Structural Engineering*, 134(6): 1006-1015

Dreger, D. (2014). Preliminary Finite Fault Results for the Aug 24, 2014 Mw 6.0 Earthquake 6 km NW of American Canyon, California Earthquake (Version 1) USGS Website at:

http://comcat.cr.usgs.gov/product/finite-fault/nc72282711/us/1409164884857/72282711.html, last visited on October 8, 2014.

Huang, M., Shakal, A., Petersen, C., Celebi, M., Hooper, J., and Klemencic R. Strong Motion Instrumentation of a 62-story Concrete Core Residential Building in San Francisco, *Proceedings of SMIP12 Seminar on Utilization of Strong-Motion Data*, October 2, 2012, pp. 81 - 96.

Huang, M., Hipley, P. and Shakal, A. (2013) Seismic instrumentation of Toll Bridges in California, Proceedings of the Seventh National Seismic Conference on Bridges & Highways, Oakland, May 20-22, 2013, Paper P10, 12 pages

Raimondo Betti, Ah Lum Hong (2008). Identification of the Baseline Modal Parameters of the Carquinez Suspension Bridge Using Ambient Vibration Data. *SMIP08 Seminar on Utilization of Strong-Motion Data*, September 28, 2008, pp. 63 – 82

USGS Earthquake Hazards Program Website, 2014 Significant Earthquakes Archive, M6.0 - 6km NW of American Canyon, California, last visited on October 7, 2014.