South Napa M 6.0 Earthquake of August 24, 2014

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1.0 Introduction

This report describes the performance of lifelines systems due to the South Napa, M 6.0 earthquake of August 24, 2014.

This report is an overview of the lifeline performance. It is based on preliminary and necessarily incomplete information. Findings in this report may change, as more information becomes available.

1.1 Outline of this Report

This report is organized into the following sections:

- Section 2 describes seismic hazards, including ground shaking, liquefaction and surface faulting.
- Section 3 describes the performance the power system.
- Section 4 describes the performance of water and wastewater systems.
- Section 5 describes the performance of highway bridges and roads.
- Section 6 describes communications.
- Section 7 covers fire following earthquake.
- Section 8 covers gas.
- Section 9 covers non-structural and other items.
- Section 10 provides references.

1.2 Key Findings

The epicenter location was south and west of urbanized Napa, California, in a rural area. The rupture from the epicenter moved northerly, resulting in about a 15 km long zone with surface rupture. At the surface, the sense of slip was primarily right lateral strike-slip, with a few locations showing minor up-tendency on the east site.

As of the time of writing this report, some 719 strong ground motion instruments have been collected and processed into "ShakeMaps". In the 2-km-wide zone either side of surface rupture, ground motions were commonly very high, with instrumental recordings showing horizontal PGA in the 0.5g to 0.6g range. In much of urban Napa, ground motions were on the order of PGA ~0.3 to 0.4g (central Napa on deep soils) to PGA ~0.25g (eastern Napa on rock).

A series of ShakeMaps were produced for this earthquake by the USGS. As of September 24, 2014, four such maps were produced, which in this report are called versions 1, 2, 3 and 4 (v1, v2, v3, and v4). As time progresses after a large earthquake more instruments "call in" their data, and the four versions use 617, 619, 665 and 719 instruments, respectively. The version 3 and 4 ShakeMaps include more instruments located close to the fault rupture, as well as the implied fault geometry, thus making for much-improved ShakeMaps in the near-field areas.

The version 3 and 4 ShakeMaps also include one instrument about 20 km south of the epicenter, with a recorded very high motion (north-south PGA = 0.97g). The version 3 and 4 ShakeMaps in this report include this instrument data, and this considerably changes the intensity of shaking south of the epicenter near Vallejo and Martinez and Carquinez. This instrumental recording shows a strong pulse at about 10 hertz. This motion is nearly 10 times higher than what would be expected at this site using median-based ground motion prediction equation (GMPE) attenuation models; but at long periods (3 seconds), the instrument shows energy levels consistent with GMPEs at 20 km. Time histories for this instrument are included in this report. A few hundred meters away, other instruments did not record this motion. The cause(s) for this high motion are still being investigated. The version 1 and 2 ShakeMaps produced, and mapped in this report, exclude this instrument; the version 3 and 4 ShakeMaps include this instrument.

Surface faulting on the order of a few inches to about a foot occurred over a the length of the rupture. Surface rupture occurred on parallel traces, separated by about 2 miles. Where surface rupture did occur, the effects (primary offset, secondary movements) were typically confined to a zone less than 100 feet wide. The vast majority of surface cracks were in areas underlain by soil, showing an "en echelon" pattern that was commonly 20 to 40 degrees (sometimes less or more) rotated clockwise (looking downwards) to the sense of fault strike. Mapping performed prior to 2014 for the area did not correctly map the location of the fault. There has been after-creep of the fault.

Liquefaction effects have not been widely observed, even though much of the area that was exposed to strong shaking was mapped as being in either Very High or High susceptible soils. Damage to buried water pipes, though, suggest that some type of PGDs did occur, including the effects of surface faulting. Future LiDAR and other mapping work may clarify the situation.

Power. About 70,000 PG&E customers lost power, affecting about 200,000 people. Essentially all power was restored within 24 hours after the earthquake. The reasons for the power outages are related to the following:

- The performance of the 60 kV – 230 kV transmission system was "superior". (essentially no functional damage). This allowed power to remain "on" during the strong shaking and for many seconds thereafter.

- As the overhead distribution circuits were energized, when wire slapping occurred, that resulted in blown fuses (cut-outs) and power outages.

- A high percentage of all power outages appear to be related to wire slapping.

- No overhead poles collapsed. About a third of all overhead poles carry one or more transformers, nearly all of which are attached to the pole using bolts. Early estimates are that about 11,000 poles were exposed to PGA > 0.2g.

Water. Potable water supply is provided by three agencies in the strong shaken areas: Napa, American Canyon and Vallejo water departments. By August 25, about 40 pipe breaks had been identified. By September 15, more than 180 water pipe breaks had been identified (with 160+ of these in the City of Napa, 25+ in the City of Vallejo). By January 2015 the number of pipe repairs was about 240 in Napa; over 50 in Vallejo. In the week following the earthquake, more than 10 pipe repair crews were working to repair water pipe breaks in Napa. As pipes were being repaired and re-pressurized, additional downstream pipe breaks were identified. There was no reported damage to water treatment plants.

Wastewater. No sewage spills are presently known. It is known that there were 10+ sewage lines damaged in the City of Napa by the earthquake; this value may change as video inspections become available. Many wine barrels toppled and broke, with the wine entering the sewage collection pipes; the high sugar content in the wine resulted in a short term "shock" to the Napa waste water treatment plant. There was no damage to the wastewater treatment plant in Sonoma Valley. There was some damage to the wastewater treatment plant in Vallejo.

Highway Bridges. Most State of California bridges performed well; most had previously been evaluated and upgraded by Caltrans. Major roads that traversed mapped liquefaction zones showed very little or no liquefaction-distress. Some local-owned bridges were damaged and had to be closed.

Communications. One communication building and one cell site in central Napa suffered some structural damage. At one site, the emergency generator reportedly did not work, so battery power was required and did work; battery power had to be supplemented by portable generators and ventilation equipment. Due to call saturation, a COW was put into service by Verizon to help the emergency response efforts by PG&E.

Gas. There was no damage to any transmission or distribution pipelines. There are gas pipes along nearly every street as there are water pipelines. The excellent performance of gas pipelines, and poor performance of water pipelines, highlights that seismic-resistant pipelines can be constructed and achieve good performance; and that water departments should start installing seismic-resistant pipelines in the future. There were thousands of service calls for gas shut-off relights and leaks on the customer side of the meter.

Fire following earthquake. 6 fire ignitions are known. At one fire, due to water pipeline damage, there was little water pressure available to control the fire. There was little wind, which helped limit fire spread.

1.3 Limitations

The findings in this reconnaissance report was developed during the first few days of the earthquake, followed up with additional assessments through February 2015. All findings must be considered accordingly. The data in this report may be incomplete, and the interpretations may be incorrect. The authors of this report make no warranty of any kind.

1.4 Acknowledgements

This report was edited by John Eidinger, with contributions by Mr. Mark Yashinsky (highway bridges), Prof. Alexis Kwasinski (telecom and power), Prof. Anshel Schiff (power), Mr. John Andrew (water and wastewater), Mr. Alex Tang (telecom and power). Comments were provided by Prof. Jon Bray. The findings of the GEER geotechnical investigation (Bray et al, 2014) has been factored into this report.

Ms. Joy Elderidge and Mr. Phil Brun of the City of Napa water department provided photos and data of the water system performance. Mr. Andrew Damon (County of Napa) provided descriptions of the performance of the Napa sewage system. Mr. Todd Arnett of PG&E provided information about the gas system. Mr. Eric Fujisaki, Mr. Raymond Trinh, Mr. Ben Chu provided information about the PG&E electric system. Mr. David Cunningham provided information about the Verizon network.

Photo credits: M. Yashinsky (Figures 5-1 through 5-18). A. Schiff (Figure 3-3). City of Napa (Figures 4-1, 4-2, 4-6, 4-7, 4-8, 4-9, 4-10, 4-14, 4-15). KGO (Figures 6-1, 6-2). Google (underlying aerial photos in Figures 2-19 and 2-20). Les Harder (Figures 8-1, 8-2, adapted from GEER 2014). C. Scawthorn (Figures 6-2, 6-3, 6-5, 6-6, 7-1, 7-2). NAPA Sanitary District (Figure 4-19). All others: John Eidinger.

1.5 TCLEE and ASCE

Soon after the 1971 San Fernando earthquake, The Technical Council of Lifeline Earthquake Engineering (TCLEE) was formed, a committee of the American Society of Civil Engineers. TCLEE was disbanded by ASCE on December 31 2014. Over a five decade period, TCLEE issued more than 60 monographs and reports and guidelines for the seismic performance, evaluation and design of lifelines. This large body of work has formed the core for nearly every standard for lifelines, used around the world. TCLEE has issued reports on lifeline performance for nearly every major destructive earthquake around the world since the 1980s, including those in the United States, Japan, China, Taiwan, Turkey, Greece, India, Philippines, Peru, Chile, Italy, as well as tsunami events (Sumatra) and major winter storms.

Beginning in 2015, ASCE intends to carry on the TCLEE legacy through a new committee that will focus on the issues of resiliency of infrastructure.

1.6 Abbreviations

ASCE	American Society of Civil Engineers
cm	centimeter
COW	Cell on Wheels
g	acceleration of gravity (= 32.2 feet / second / second = 981 gal)
G&E	G&E Engineering Systems Inc.
km	kilometer
kV	kilovolts
M	Magnitude (moment magnitude unless otherwise noted)
MGD	Million gallons per day (U.S. measure)
PGA	Peak Ground Acceleration, g
PGD	Permanent Ground Displacement, (inches or cm)
PGV	Peak Ground Velocity (measured in inches/second or cm/sec)
PG&E	Pacific Gas and Electric
SERA	System Earthquake Risk Assessment
TCLEE	Technical Council on Lifeline Earthquake Engineering
USGS	United States Geological Survey

1.7 Units

This report makes use of both common English and SI units of measure.

Common Conversions

1 kip = 1,000 pounds

1 foot = 12 inches

1 inch = 25.4 mm = 2.54 cm

1 mile = 1.609347 kilometers

1 pound-force = 4.448 newtons

1 pound = 0.453592 kilogram

1 psi = 6.894757 kiloPascal (kPa)

1 kPa = 0.145038 psi

1 m = 1,000 mm = 100 cm

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2.0 Seismic Hazards

Section 2 describes the seismic hazards in this earthquake.

- Section 2.1 provides maps showing the location of the earthquake, major population centers, an overview of the ground shaking levels.
- Section 2.2 describes the geologic conditions and liquefaction susceptibility of the Napa and north San Francisco Bay region.
- Section 2.3 provides maps showing PGA, PGV, and Spectra Accelerations in the Napa area.
- Section 2.4 provides listings of ground motion values (PGA, PGV, Spectra) at all PG&E substations in the strong shaking areas.
- Section 2.5 examines the observed surface faulting.
- Section 2.6 discusses the accuracy of ShakeMaps.

2.1 Location of the Earthquake

At 3:20 am, Pacific time, on August 24, 2014, an earthquake occurred near the city Napa, California. Figure 2-1 shows a map of the region, with major places and populations, along with a map[1] of the level of ground shaking.

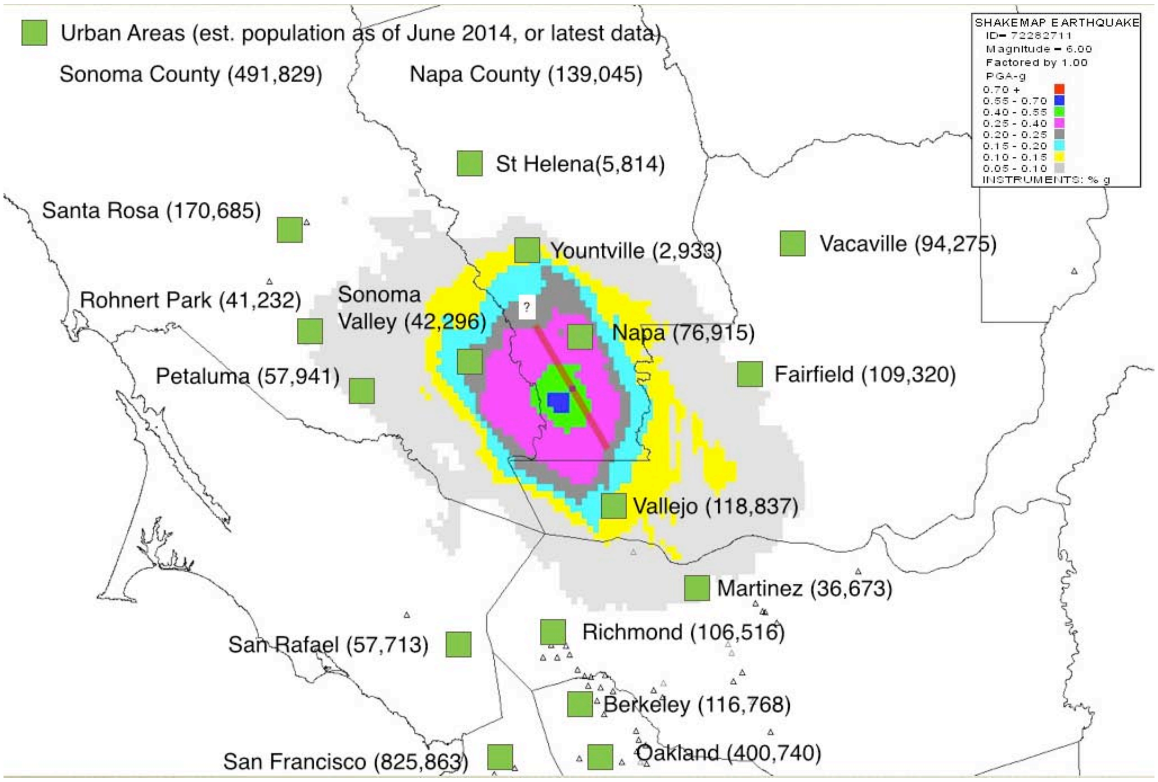


Figure 2-1. Place Names and Populations, SERA ShakeMap-v1 (PGA)

In Figure 2-1, the bright blue "dot" corresponds to an early interpretation of the location of the epicenter of the earthquake; the green squares represent the major population centers (population in brackets). The colors of the shaking correspond to:

- Blue. PGA = 0.55g+
- Green. PGA 0.40g – 0.55g
- Magenta. PGA 0.25g to 0.40g
- Dark Grey. PGA 0.20g to 0.25g.

[1] All ShakeMaps in this report were prepared using SERA. This map shows PGA, maximum of NS and EW components, based on a ShakeMap using 617 recording instruments (Version 1). Other maps and tables rely on version 2 (619 reporting instruments) or version 3 (665 reporting instruments) or version 4 (719 reporting instruments).

- Cyan. PGA 0.15g to 0.20g.
- Yellow. PGA 0.10g to 0.15g.
- Light Grey. PGA 0.05g to 0.10g.
- White (no color). PGA < 0.05g.

Figure 2-2a shows the version 3 ShakeMap, produced August 29, 2014, and Figure 2-2b shows the version 4 ShakeMap, Produced September 19, 2014. In these versions, the fault geometry is incorporated into the ShakeMap, as well as additional recording stations as compared to versions 1 and 2. Importantly, more than 40 additional instruments (version 3) and 100 instruments (version 4) are included that were not available for the first ShakeMap. The following highlights some key instruments.

- Instrument (CE.68206) recorded PGA = 0.97g (North South), 0.51g (East West) and 0.32g (Vertical). This instrument is located 20 km from the epicenter; given the distance to the epicenter, the meaning of this very high PGA level is still being reviewed. The impact of this instrument probably greatly distorts the true PGA map suitable for Vallejo and points south.
- Instrument (NC.N016) recorded PGA = 0.65g (North South), 0.32g (East West) and 0.24g (Vertical). This instrument is plotted as a red dot in Figure 2-4. This instrument is located 3.9 km from the epicenter.
- Instrument (NC.N019B) recorded PGA = 0.28g (North South), 0.37g (East West) and 0.18g (Vertical). This instrument is plotted as a blue dot in Figure 2-4. This instrument is located 6.1 km from the epicenter.

The extra instrument recordings strongly influence the PGA map towards Vallejo and Martinez. The additional of fault geometry also strongly influences the PGA map near Napa.

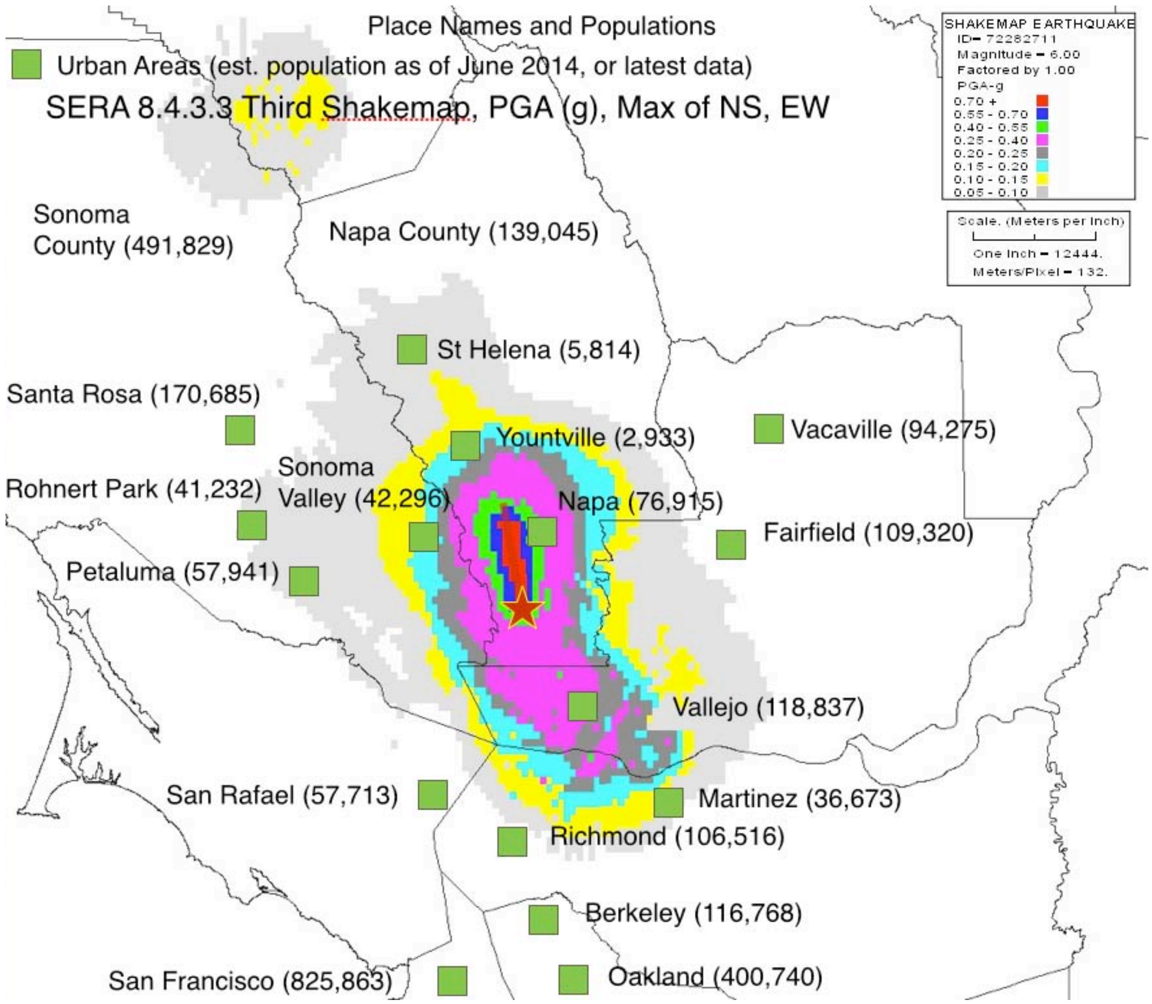


Figure 2-2a. Place Names and Populations, SERA ShakeMap-3 (PGA)

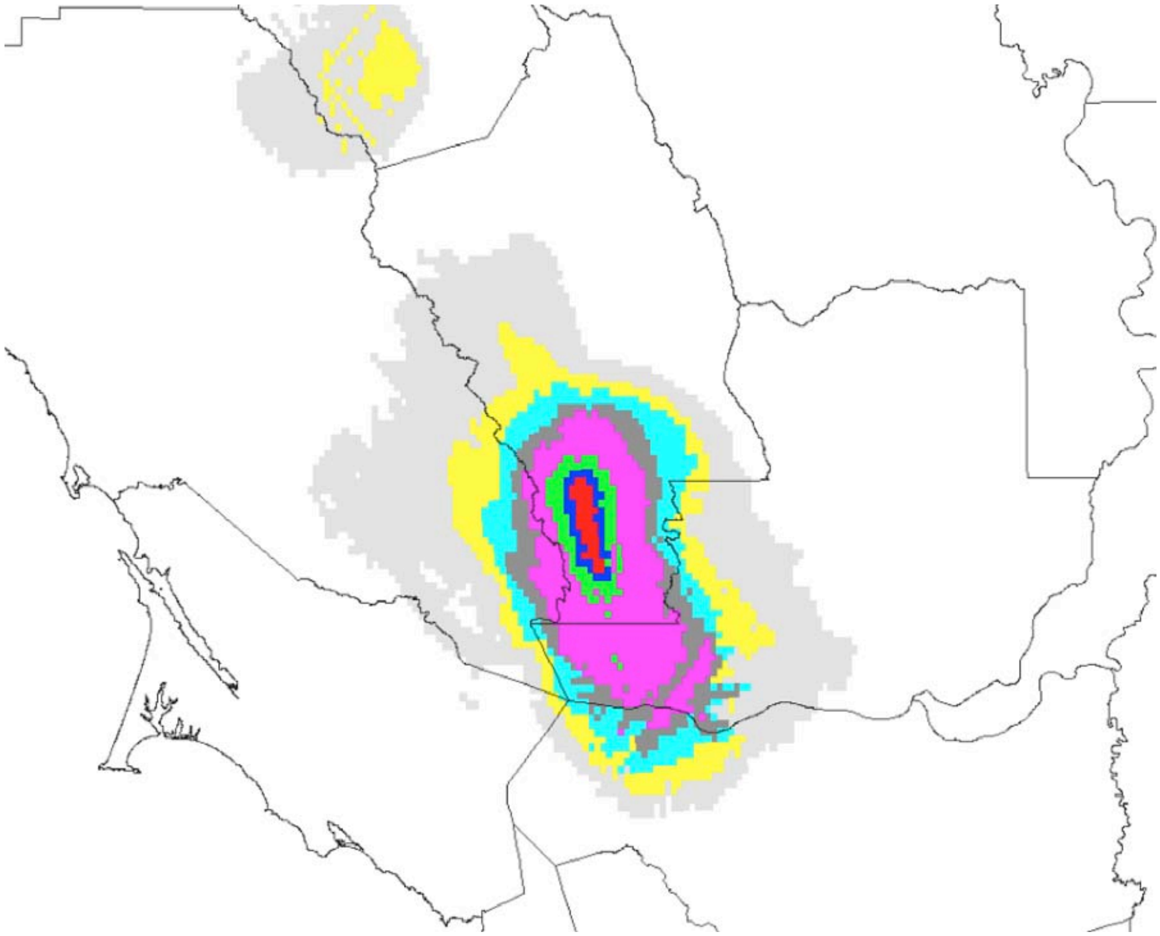


Figure 2-2b. Place Names and Populations, SERA ShakeMap-4 (PGA)

Comparing versions 3 and 4 maps, there is generally little differences. However, as noted before, one anomalous instrument value greatly distorts the true PGA map for Vallejo and points south.

Figure 2-3 shows the underlying data from strong motion instruments that produced the map in Figure 2-1. In preparing this map, a total of 617 strong motion instruments recorded the earthquake. In Figures 2-3 and 2-4, the small dots show the location of each instrument. For instruments that recorded motions higher than PGA = 0.05g, colored dots are plotted, using the same scale as in Figure 2-1. Using attenuation models, default soil maps and the estimated location of the epicenter, the USGS ShakeMap software interpolates between the dots (fewer than 100 within the mapped area of the ShakeMap) in Figure 2-3 to produce the shaking map in Figure 2-1 (more than 60,000 grid cells). About 99.8% of the shaking map data in Figure 2-1 is based on some form of interpolation.

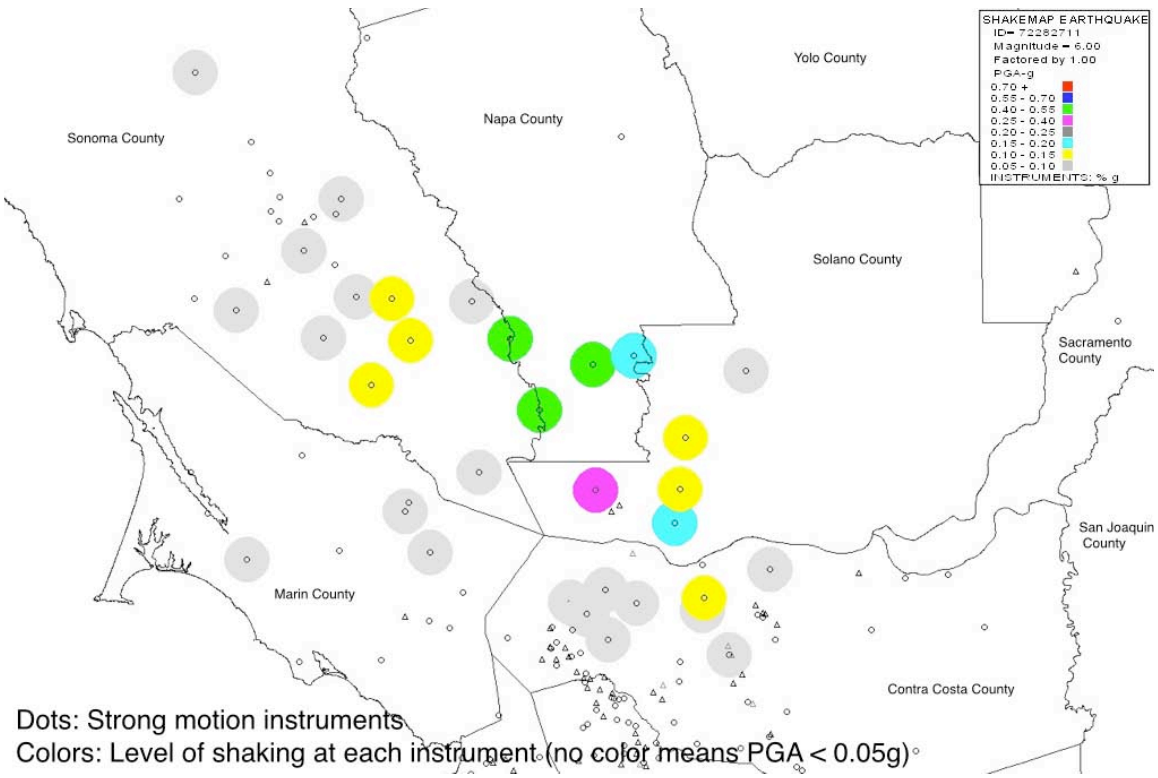


Figure 2-3. Strong Motion Instruments (PGA)

Figure 2-4 shows the underlying data from strong motion instruments that produced the map in Figure 2-2a. In preparing this map, a total of 665 strong motion instruments recorded the earthquake. Using attenuation models, and the assumed fault geometry, and default soil maps and the estimated location of the epicenter, the USGS ShakeMap software interpolates between the dots in Figure 2-4 to produce the shaking map in Figure 2-2a. The instrument that produced the (possibly anomalous) PGA = 0.97g value is "mostly hidden" under another instrument dot that is plotted as "green".

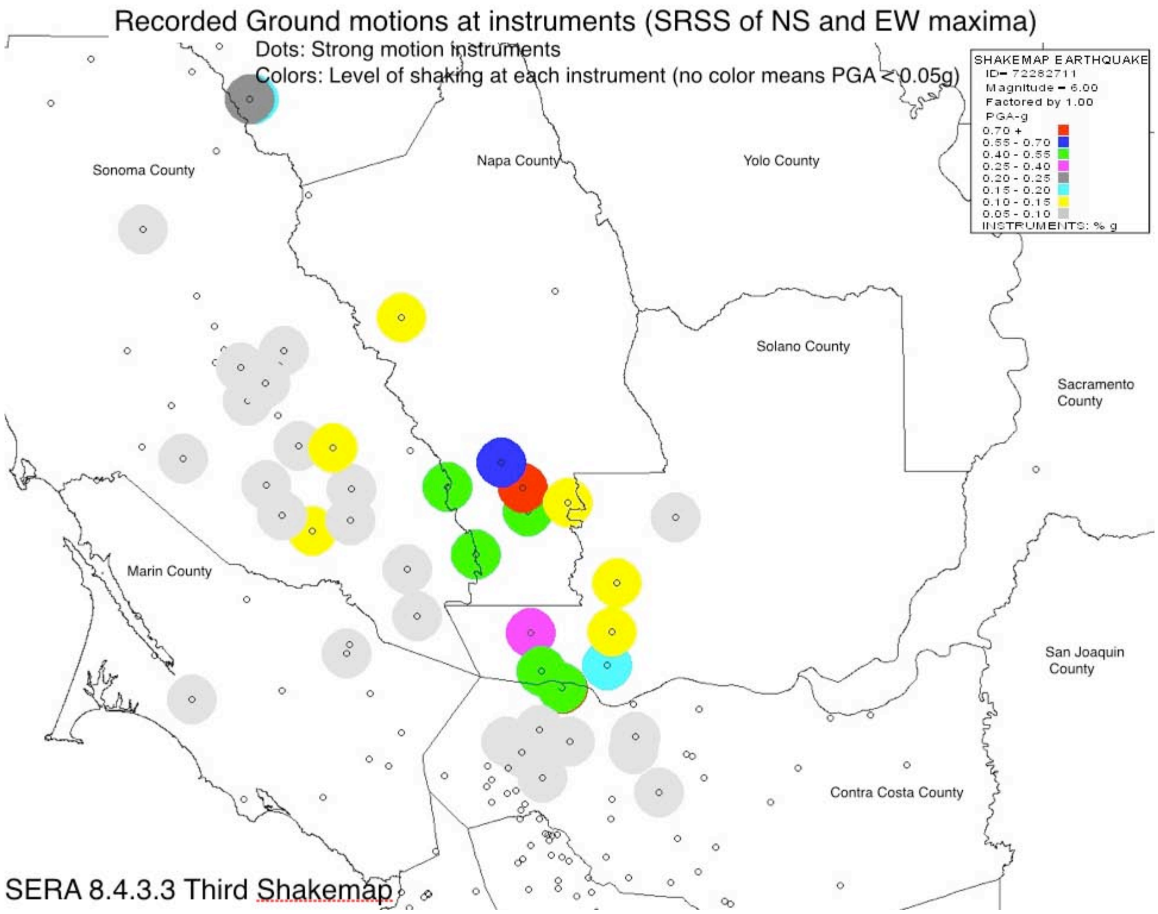


Figure 2-4. Strong Motion Instruments (version 3) (PGA)

The actual fault geometry is not used in producing the ShakeMap in Figure 2-1. The red line in Figure 2-1 is a preliminary interpretation of the actual fault rupture. Once the fault rupture location is better quantified, updated ShakeMaps will tend to remove the "bulls-eye" directly over the epicenter, and replace it with strong shaking that emanates more regularly from either side of the fault rupture; this is clearly seen in Figures 2-2a, b.

Figure 2-5 shows the known active faults in the region. Based on preliminary interpretation, it appears that the West Napa fault caused the August 24 2014 earthquake. The red lines correspond to the locations of active faults in the USGS 2008 database of Quaternary active faults, as used in preparation of U. S. National seismic hazard maps, such as those used in the 2012 IBC. While these red lines are accurate enough for preparation of national ground shaking hazard maps, they are not detailed enough for local assessments of surface faulting hazards.

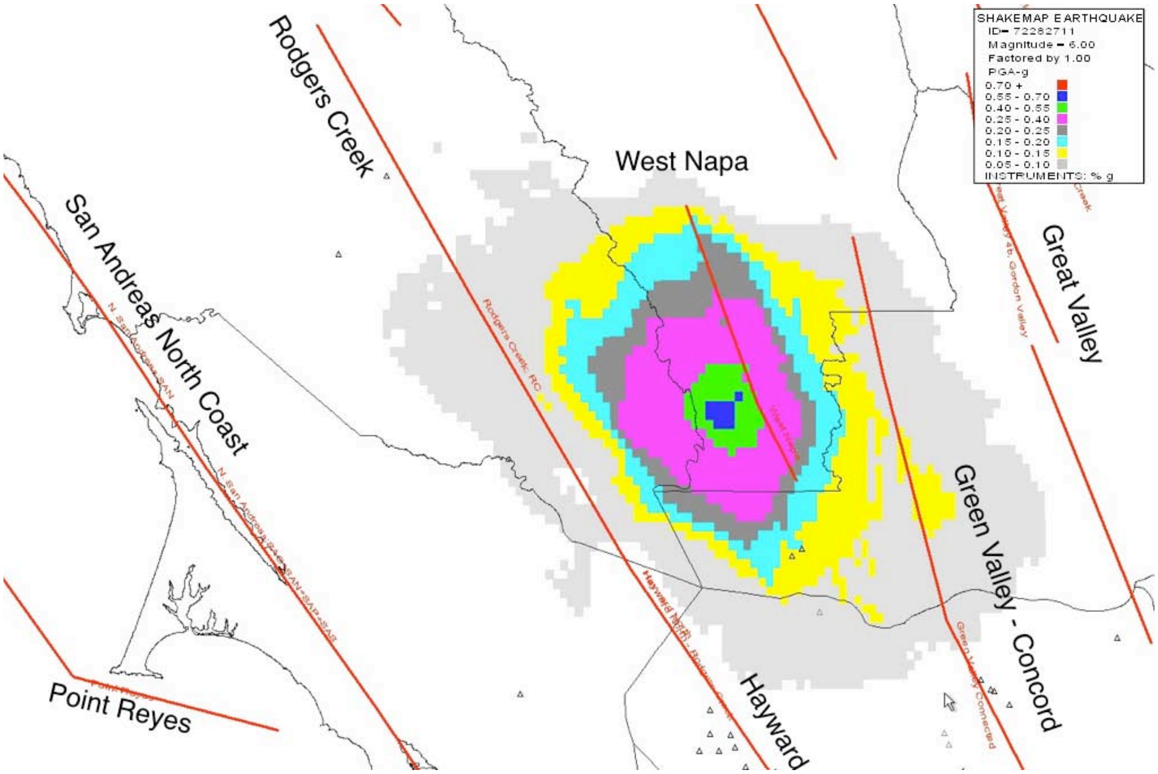


Figure 2-5. Nearby Active Faults

2.2 Geologic Conditions and Liquefaction Susceptibility

Figure 2-6 shows a geologic map of the Napa area. This geologic map was prepared by Sowers et al (1998).

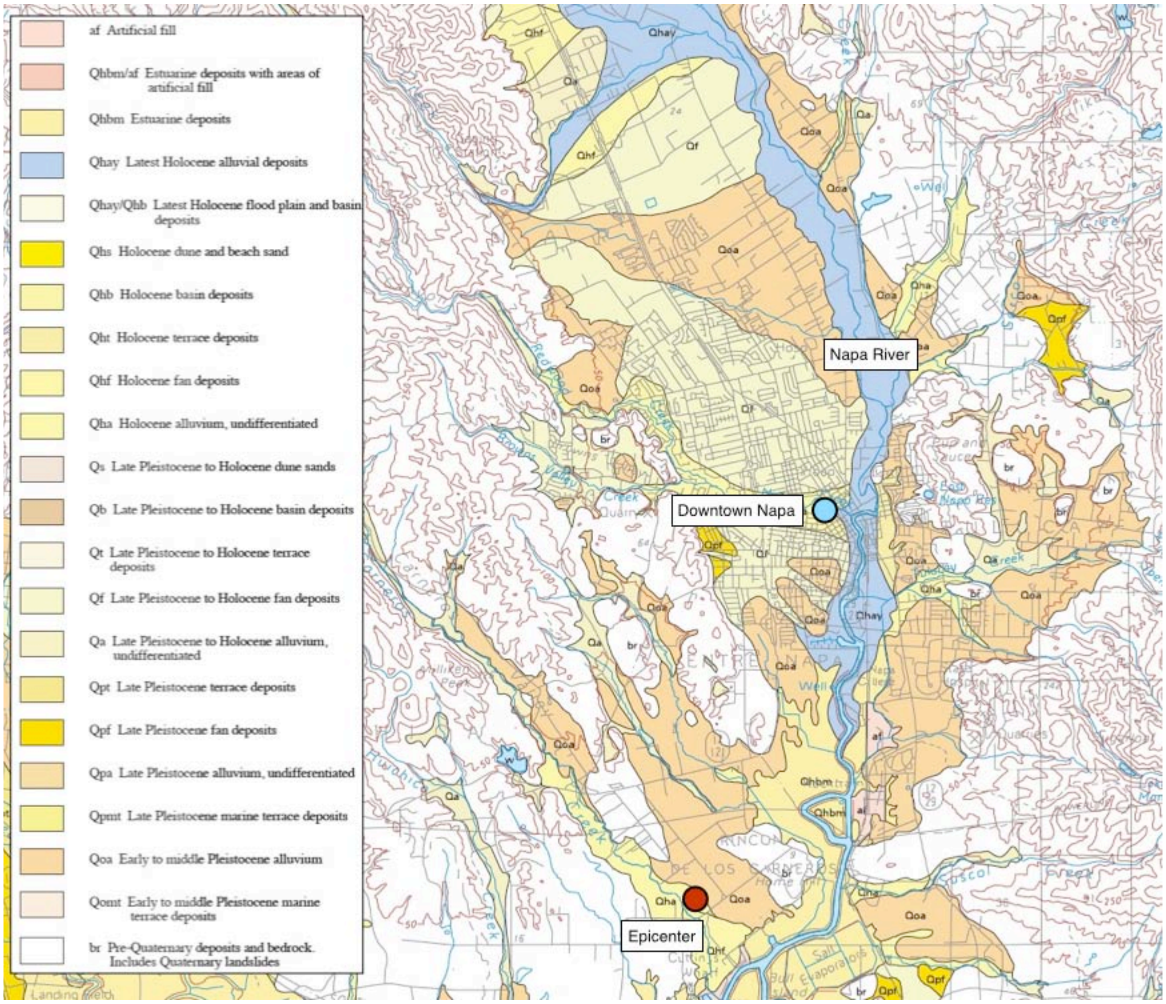


Figure 2-6. Geologic Map (After Sowers, 1998)

In preparing the map, Sowers et al were particularly concerned by the geologic conditions of greatest concern that can lead to liquefaction:

- Holocene estuarine deposits
- Holocene stream deposits
- Eolian sands
- Artificial fills

In developing this geologic map, Sowers et al first interpreted aerial photographs and topographic maps to determine the depositional environment and to estimate relative age by evaluating landforms and geomorphic relationships. Second, published soil survey data (dated 1956 through 1985) was reviewed to assess the character and age of near-surface deposits.

Figures 2-7 and 2-8 show the liquefaction susceptibility map for the San Francisco and Napa areas (after Knudsen 2000 and Witter 2006), respectively. In these maps, red = very high; pink = high; yellow = moderate; green = low; grey = non / very low; white = none / not mapped; heavy red line = West Napa fault location.

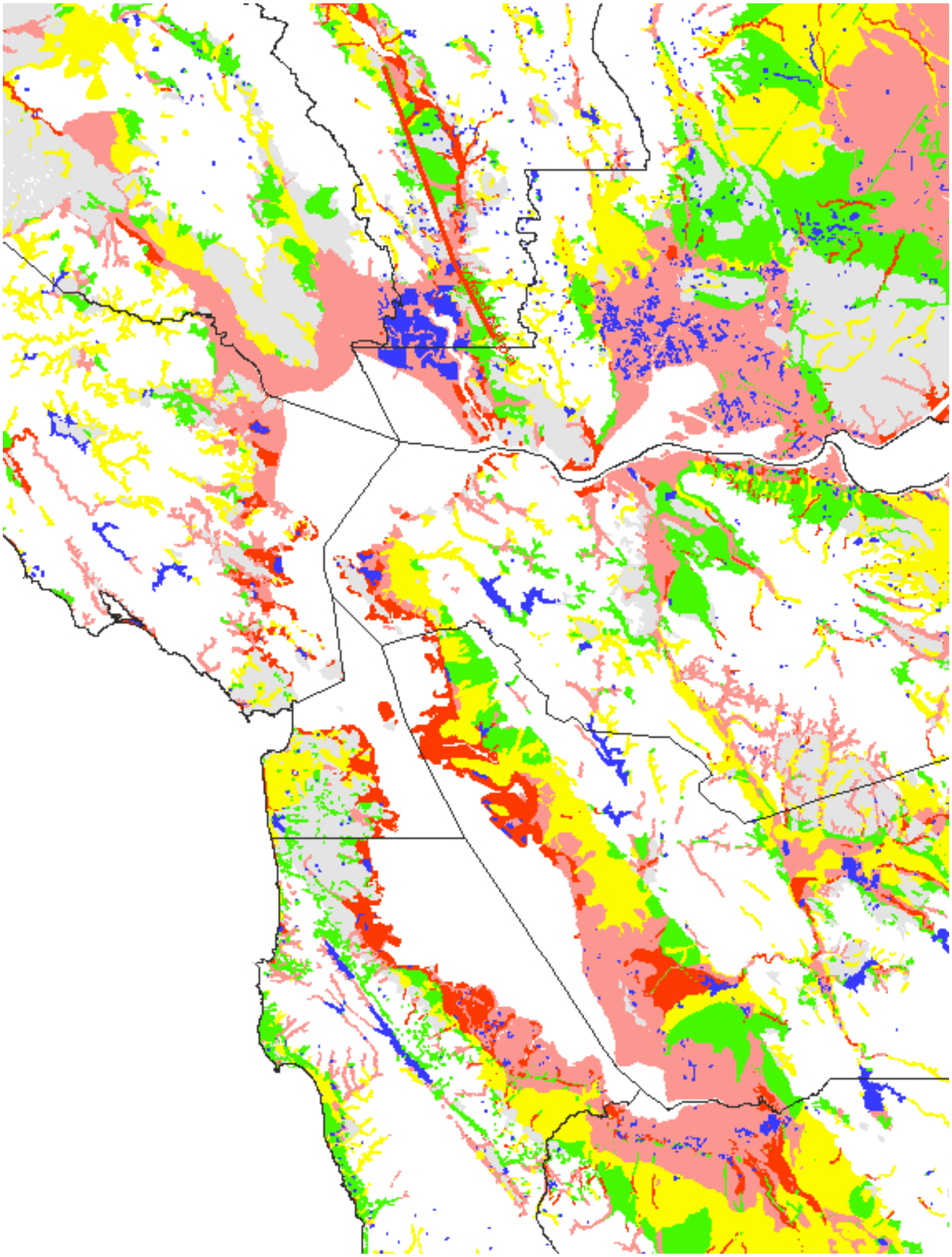


Figure 2-7. Liquefaction Susceptibility Map, San Francisco Bay Area

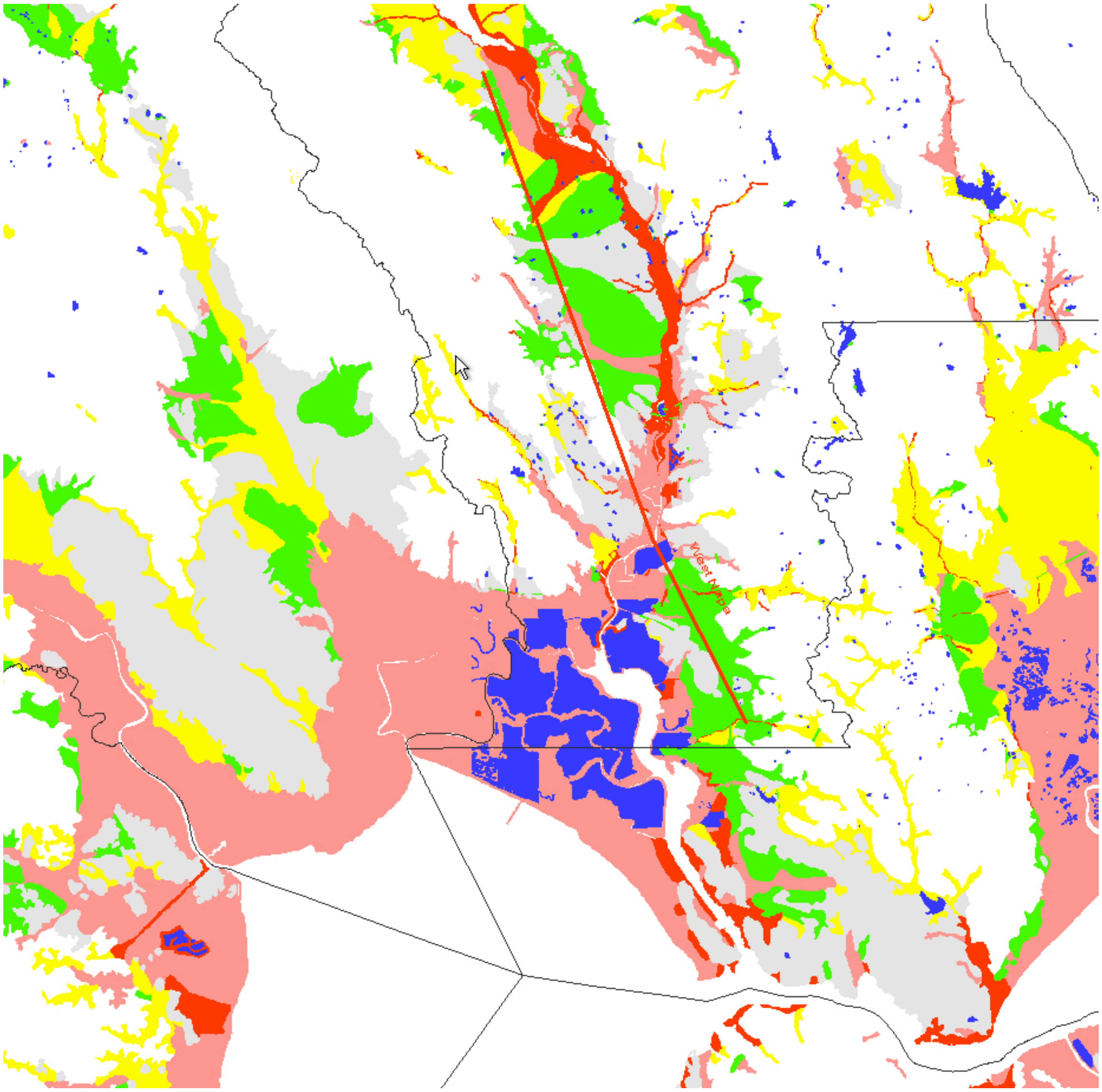


Figure 2-8. Liquefaction Susceptibility Map, Napa and Sonoma Valley Area

By examining Figures 2-6, 2-7 and 2-8 (surface geology and liquefaction maps) and Figures 2-1 and 2-2 (PGA), one might expect that perhaps 20% to 40% of the areas mapped as being Holocene (young) and exposed to PGA > 0.3g, should have shown evidence of liquefaction. Initial maps of water pipe leaks in Napa would seem to validate this; however, initial assessment at the ground level by teams of geologists have not (yet) shown widespread effects of liquefaction in these areas. With regards to liquefaction, the following (initially) can be surmised:

- The low magnitude of this earthquake (M 6.0) results in relatively short duration of very strong shaking (PGA > 0.2g). Liquefaction in moderate to high susceptible soils tends to be triggered at PGA > 0.15g at a minimum (sometimes PGA > 0.3g), and the short duration results in small settlements (volumetric strains) or lateral spreads, even where liquefaction occurs.

- The underlying liquefaction susceptibility map includes "High" and "Very High" zones for locations with very different soils: both loose sandy / gravelly soils (such as very near the banks of the Napa River), as well as locations with young Bay muds (north of San Pablo Bay). Young Bay muds are very weak clays, and could fail under very high magnitude (such as M 7.5 events) due to shear strain failure, with attendant slumps, but not much at M 6.0; if these muds are not interbedded with sandy lenses, there may be very modest / small permanent movements at M 6.0, although moderate large transient displacement might still occur.

2.3 SERA Listings of ShakeMap Ground Motions

Figure 2-9 shows the SERA ShakeMap header information. This shows the event ID (72282711), time, magnitude and estimated epicenter of the event, the boundaries (in UTM Zone 10 coordinates) within which ShakeMaps are computed, and the time the data was processed by the USGS (in this case, Sunday Aug 24 2014 at 22:21:05.) Over time, as more data becomes available, USGS recomputes the instrumented data and resulting ShakeMaps, and the older versions of the data are removed from the USGS web site. Earlier on August 24, USGS first released a ShakeMap that was processed at 16:21:29. Figure 2-10 shows the second data set. Between the first and second datasets, the epicenter was moved about 800 meters, and more instruments reported in (619 total), with more processing of data for all instruments. Between the second and third datasets, more instruments were added (655 total), and the fault geometry was defined.

As time progresses, the ShakeMaps will tend to get refined and improved. Note: USGS tends to repeat the ShakeMap processing only for larger events (such as this earthquake), whereas for smaller events, USGS generally only releases one ShakeMap.

```
 *** THE FOLLOWING ANALYSES ARE FOR A SHAKEMAP-GENERATED EARTHQUAKE SCENARIO

72282711 6.0 38.22 -122.31 AUG 24 2014 10:20:44 UTC -123.563 37.3869 -121.063
 ------------------------------------------------------------
 SHAKEMAP GRID.XYZ FILE INFORMATION FOLLOWS
 ------------------------------------------------------------
 NAME/CUSPID OF EVENT     =      72282711
 MAGNITUDE   OF EVENT     =           6.00
 LATITUDE    OF EPICENTER =        38.2200 decimal degrees
 LONGITUDE   OF EPICENTER =      -122.3100 decimal degrees (west negative)
 MONTH       OF EVENT     =      AUG
 DAY         OF EVENT     =      24
 YEAR        OF EVENT     =      2014
 TIME        OF EVENT     =      10:20:44 hours:minutes:seconds
 TIME ZONE                =      UTC (GMT = Greenwich Mean Time)

 ------------------------------------------------------------
 SHAKEMAP GRID.XYZ DATA BOUNDARY INFORMATION FOLLOWS
 ------------------------------------------------------------
 WEST  BOUNDARY     =      -123.5630 decimal degrees longitude
 SOUTH BOUNDARY     =        37.3869 decimal degrees latitude
 EAST  BOUNDARY     =      -121.0630 decimal degrees longitude
 NORTH BOUNDARY     =        39.0535 decimal degrees latitude

 ----------------------------------------------------------------------
 THIS SHAKEMAP DATA WAS PROCESSED BY USGS/CGS/U.W. AT THE FOLLOWING TIME
 ----------------------------------------------------------------------
 PROCESS DAY        = Sun
 PROCESS MONTH      = Aug
 PROCESS DATE       =  24
 PROCESS HH:MM:SS   = 22:21:05
 PROCESS YEAR       = 2014
 PROCESS NAME       = 6.8 km (4.2 mi) NW of American

 ------------------------------------------------------------
 EASTINGS     OF EPICENTER =         560399 Meters. UTM Zone 10 1983
 NORTHINGS    OF EPICENTER =        4230449 Meters. UTM Zone 10 1983
```

Figure 2-9. ShakeMap-v2 Data

```
72282711 6.0 38.22 -122.31 AUG 24 2014 10:20:44 UTC -123.563 37.3869 -121.
 -----------------------------------------------------------
 SHAKEMAP GRID.XYZ FILE INFORMATION FOLLOWS
 -----------------------------------------------------------
 NAME/CUSPID OF EVENT     =      72282711
 MAGNITUDE   OF EVENT     =          6.00
 LATITUDE    OF EPICENTER =        38.2200 decimal degrees
 LONGITUDE   OF EPICENTER =      -122.3100 decimal degrees (west negative)
 MONTH       OF EVENT     =      AUG
 DAY         OF EVENT     =      24
 YEAR        OF EVENT     =      2014
 TIME        OF EVENT     =      10:20:44 hours:minutes:seconds
 TIME ZONE                =      UTC (GMT = Greenwich Mean Time)

 ------------------------------------------------------------
 SHAKEMAP GRID.XYZ DATA BOUNDARY INFORMATION FOLLOWS
 ------------------------------------------------------------
 WEST  BOUNDARY     =      -123.5630 decimal degrees longitude
 SOUTH BOUNDARY     =        37.3869 decimal degrees latitude
 EAST  BOUNDARY     =      -121.0630 decimal degrees longitude
 NORTH BOUNDARY     =        39.0535 decimal degrees latitude

 ----------------------------------------------------------------------
 THIS SHAKEMAP DATA WAS PROCESSED BY USGS/CGS/U.W. AT THE FOLLOWING TIME
 ----------------------------------------------------------------------
 PROCESS DAY        = Fri
 PROCESS MONTH      = Aug
 PROCESS DATE       =  29
 PROCESS HH:MM:SS   = 12:44:42
 PROCESS YEAR       = 2014
 PROCESS NAME       = 6.8 km (4.2 mi) NW of American

 -------------------------------------------------------------
 EASTINGS     OF EPICENTER =        560399 Meters. UTM Zone 10 1983
 NORTHINGS    OF EPICENTER =       4230449 Meters. UTM Zone 10 1983
```

Figure 2-10. ShakeMap-v3 Data

Figure 2-11 shows the distances between the epicenter and the mapped faults (from Figure 2-5). In this event, SERA shows that the most likely causative fault is the West Napa fault, with the estimated epicenter being 2.3 km from the mapped fault (surface projection). From Figure 2-11, one could surmise the fault was on the West Napa fault, as it is closest to the epicenter (2.3 km). As observed in this earthquake, the prior mapping of the West Napa by USGS (and others) was off by about 2 km, with surface rupture occurring where no fault had been mapped. This has implications as to the seismic design of pipelines that are meant to traverse faults, in that if the fault is not accurately mapped, the pipeline design may be wrong.

```
---------------------------------------------------------------
For faults within 75 km of the epicenter,
the USGS-provided epicenter for this SHAKEMAP event
is calculated by SERA to be:
---------------------------------------------------------------
   46.1 kM from fault number   2. N. San Andreas;SAN
   53.5 kM from fault number   3. N. San Andreas;SAP
   46.1 kM from fault number   5. N. San Andreas;SAO+SAN
   53.5 kM from fault number   6. N. San Andreas;SAP+SAS
   46.1 kM from fault number   7. N. San Andreas;SAO+SAN+SAP
   46.1 kM from fault number   8. N. San Andreas;SAN+SAP+SAS
   46.1 kM from fault number   9. N. San Andreas;SAO+SAN+SAP+SAS
   18.3 kM from fault number  10. Hayward North
   44.4 kM from fault number  11. Hayward South
   18.3 kM from fault number  12. Hayward North + South
   16.8 kM from fault number  13. Rodgers Creek; RC
   16.8 kM from fault number  14. Hayward North - Rodgers Creek
   16.8 kM from fault number  15. Hayward-Rodgers Creek;RC+HN+HS
   51.9 kM from fault number  16. Calaveras;CN
   51.9 kM from fault number  19. Calaveras;CN+CC
   51.9 kM from fault number  21. Calaveras;CN+CC+CS
   15.0 kM from fault number  22. Green Valley Connected
   56.1 kM from fault number  23. Greenville Connected
   44.9 kM from fault number  24. Mount Diablo Thrust
   55.2 kM from fault number  29. Point Reyes
    2.3 kM from fault number  31. West Napa
   27.7 kM from fault number  32. Hunting Creek-Berryessa
   56.9 kM from fault number  33. San Gregorio Connected
   70.0 kM from fault number 115. Collayomi
   56.9 kM from fault number 178. Great Valley 3, Mysterious Ridge
   44.0 kM from fault number 180. Great Valley 4a, Trout Creek
   30.1 kM from fault number 181. Great Valley 5, Pittsburg Kirby
   51.7 kM from fault number 193. Maacama-Garberville
   32.2 kM from fault number 210. Great Valley 4b, Gordon Valley
   56.9 kM from fault number 219. San Gregorio Connected
```

Figure 2-11. Distance to faults within 75 km of epicenter (v2, v3)

Figure 2-12 shows a sample listing the raw ShakeMap-3 data produced by the USGS. This "raw" data is included in the file "grid.xyz" that is produced by the USGS. In this case, the "grid.xyz" file has 60,501 entries, each computed at a latitude / longitude pair. For this event, six parameters are computed at each point: PGA, PGV, MMI, PSA03 (T = 0.3 seconds, 5% damping); PSA10 (T = 1.0 seconds, 5% damping), PSA30 (T = 3.0 seconds, 5% damping). Each value is meant to represent the maximum of NS and EW motions (excluding vertical).

There are many steps in developing this data. Essentially, the instrument data are deconvoluted to "equivalent rock". Then the "equivalent rock" data is extrapolated to a regular set of grid points (the latitude / longitude pairs in Figure 2-12). Then, the "equivalent rock" motions are re-convoluted to the surface, assuming a soil map for each grid point. The soil map in ShakeMap is based on indirect computation of likely soil conditions based on local slope. The soil deconvolution and reconvolution factors are based on simplified "bump up" factors commonly adopted in codes. The attenuation model in ShakeMap is currently a single model, circa 2007.

After going through this process, the minimum and maximum of the ShakeMap are listed at the bottom of Figure 2-12. For example, the maximum ShakeMap PGA value is 85.32 (0.8532g) [for ShakeMap-2 data, the corresponding values were 64.37 (0.6437g)]. This value reflects that there are usually no instruments directly over the fault (epicenter), so the ShakeMap "back-calculates" the assumed motions at the epicenter (and in versions 3 and 4, to the assumed fault rupture) using attenuation models, interpolations and assumed soil profiles. Even with all these assumptions, the resulting ShakeMaps that use these 60,501 points are often interpreted as being extremely "accurate", as a) they come from the USGS, and b) they are based on instruments. In fact, no more than about 1% of ShakeMap grids points have "accurate" instrumental data (655 instruments produced 60,501 grid points, and most of the instruments are outside the grid boundaries); and even within a grid point that has a instrument, many studies show that variation in high frequency content of spectra (such as PGA, and SA(T=0.3 seconds)), varies considerably even over distances as short as 100 meters.

RAW SHAKEMAP DATA FOLLOWS (First 10 + last 10 records plus min and max)

LONGITUDE decimal degrees	LATITUDE decimal degrees	PGA percent g	PGV cm/sec	MMI Units	PSA03 percent g	PSA10 percent g	PSA30 percent g	(5%) (damping)
-123.5628	39.0535	0.2300	0.5600	1.7500	0.6600	0.4500	0.2200	1
-123.5545	39.0535	0.2500	0.6200	1.7900	0.6800	0.4800	0.2200	2
-123.5461	39.0535	0.2600	0.6800	1.8300	0.7000	0.5200	0.2300	3
-123.5378	39.0535	0.2700	0.7300	1.8800	0.7000	0.5400	0.2300	4
-123.5295	39.0535	0.2700	0.7800	1.9300	0.7000	0.5600	0.2400	5
-123.5211	39.0535	0.2800	0.8100	1.9700	0.6900	0.5700	0.2400	6
-123.5128	39.0535	0.2800	0.8200	1.9900	0.7000	0.5800	0.2400	7
-123.5045	39.0535	0.2800	0.8200	2.0000	0.7000	0.5800	0.2400	8
-123.4961	39.0535	0.2800	0.8300	2.0000	0.7100	0.5800	0.2500	9
-123.4878	39.0535	0.2900	0.8300	2.0100	0.7100	0.5900	0.2500	10
-121.1378	37.3869	0.3600	0.5800	2.1600	1.2800	0.7700	0.1900	60492
-121.1295	37.3869	0.3600	0.6000	2.1800	1.2900	0.7800	0.2000	60493
-121.1211	37.3869	0.3600	0.6000	2.1800	1.3000	0.7900	0.2000	60494
-121.1128	37.3869	0.3600	0.6000	2.1700	1.2900	0.7900	0.2000	60495
-121.1045	37.3869	0.3600	0.6000	2.1600	1.2800	0.7800	0.2000	60496
-121.0961	37.3869	0.3500	0.5900	2.1500	1.2700	0.7800	0.2000	60497
-121.0878	37.3869	0.3500	0.5900	2.1400	1.2600	0.7800	0.2000	60498
-121.0795	37.3869	0.3500	0.5900	2.1300	1.2600	0.7800	0.2000	60499
-121.0711	37.3869	0.3500	0.6200	2.1400	1.2800	0.8100	0.2100	60500
-121.0628	37.3869	0.3600	0.6600	2.1800	1.3200	0.8700	0.2200	60501
-123.5628	37.3869	0.2100	0.3600	1.7500	0.4700	0.3900	0.1000	MINIMUM
-121.0628	39.0535	85.3200	95.9000	8.7600	146.0300	91.0600	27.1900	MAXIMUM

Figure 2-12. Raw ShakeMap Grid Data (v3)

Therefore, as a rule of thumb, unless situated immediately at an instrument location, ShakeMap grid data should usually be considered to be no more accurate than about ±50%.

Figure 2-13 shows the ShakeMap station list header.

```
-------------------------------------------------------------
SHAKEMAP STATIONLIST.TXT FILE INFORMATION FOLLOWS
-------------------------------------------------------------
NAME/CUSPID OF EVENT     =      72282711
DATE        OF EVENT     =      2014-08-24
TIME        OF EVENT     =      10:20:44 hours:minutes:seconds
TIME ZONE                =      UTC (GMT = Greenwich Mean Time)
MAGNITUDE   OF EVENT     =      M=6.0
LATITUDE    OF EPICENTER =        38.2202 decimal degrees
LONGITUDE   OF EPICENTER =      -122.3128 decimal degrees (west negative)
DEPTH       OF EVENT     =      11.25    km
```

Figure 2-13. ShakeMap Instrument Station List Header (v 1 v 2 v 3)

Figure 2-14 provides an example of a formatted listing for the instrument data. Each instrument (one instrument per row) can provide up to 23 fields of data:

- Station code
- Longitude, Latitude
- Epicentral distance
- Network Code
- Channel description (NS, 3) or (EW 2) or (VT, 1)
- For each channel, PGV, PGA, PSA03, PSA10, PSA30

RAW STATIONLIST DATA FOLLOWS (First 2000 stations)

STATION CODE	LONGITUDE decimal degrees	LATITUDE decimal degrees	EPICENTER DISTANCE km	NTWK CODE	CH NS 3	PGV cm/ sec	PGA % g	PSA03 % g	PSA10 % g	PSA30 % g
AZ.BZN	33.4915	-116.6670	728.3	AZ	HHN	0.0013	0.0010	0.0049	0.0020	0.0007
AZ.CRY	33.5654	-116.7373	717.8	AZ	HHN	0.0008	0.0004	0.0011	0.0011	0.0004
AZ.FRD	33.4947	-116.6022	732.1	AZ	HHN	0.0010	0.0004	0.0006	0.0013	0.0006
AZ.KNW	33.7141	-116.7119	707.4	AZ	HHN	0.0075	0.0009	0.0011	0.0015	0.0026
AZ.PFO	33.6117	-116.4594	731.8	AZ	HHN	0.0062	0.0009	0.0009	0.0014	0.0011
AZ.RDM	33.6300	-116.8478	705.6	AZ	HHN	0.0072	0.0007	0.0009	0.0015	0.0015
AZ.SCI2	32.9150	-118.4879	680.6	AZ	HNN	0.0048	-1.0000	0.0034	0.0022	0.0019
AZ.SMER	33.4577	-117.1708	700.4	AZ	HHN	0.0012	0.0004	0.0008	0.0007	0.0003
AZ.SND	33.5519	-116.6129	726.8	AZ	HHN	0.0012	0.0005	0.0010	0.0022	0.0010
AZ.SOL	32.8410	-117.2480	750.2	AZ	HHN	0.0146	-1.0000	0.0015	0.0031	0.0015
AZ.WMC	33.5736	-116.6747	721.1	AZ	HHN	0.0014	0.0010	0.0021	0.0022	0.0007
BG.DRH	38.8236	-122.9527	84.1	BG	CNN	0.8713	0.8108	1.6466	1.6082	0.0000
BK.BDM	37.9540	-121.8655	46.0	BK	HNN	1.2759	0.5881	2.0603	1.3425	0.2632
BK.BKS	37.8762	-122.2356	35.8	BK	HNN	0.9463	0.8069	2.3673	1.3654	0.3813
BK.BL67	37.8749	-122.2432	35.9	BK	HNN	1.1459	1.8791	4.1169	1.0337	0.3819
BK.BL88	37.8772	-122.2543	35.5	BK	HNN	1.1180	1.4273	2.7178	1.9207	0.3120
BK.BRIB	37.9189	-122.1518	33.3	BK	HNN	1.2245	1.0762	1.7371	1.7210	0.3222
BK.CMB	38.0346	-120.3865	166.7	BK	HHN	0.0700	0.0474	0.1347	0.0658	0.0204
BK.CVS	38.3453	-122.4584	15.9	BK	HNN	-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
BK.FARB	37.6978	-123.0011	80.7	BK	HNN	0.4616	0.4720	1.3686	0.6506	0.0697
BK.GASB	39.6547	-122.7160	160.2	BK	HNN	0.2378	0.0585	0.0645	0.1367	0.0942
BK.HAST	36.3887	-121.5514	211.4	BK	HNN	0.1144	0.0598	0.1372	0.1764	0.0218
BK.HATC	40.8161	-121.4612	294.7	BK	HNN	0.0934	0.0313	0.0325	0.0787	0.0744
BK.HELL	36.6801	-119.0228	334.1	BK	HHN	0.0307	0.0123	0.0238	0.0258	0.0066
BK.HOPS	38.9935	-123.0723	105.3	BK	HNN	0.8396	0.2321	0.2403	0.5388	0.4632
BK.HUMO	42.6071	-122.9567	487.8	BK	HHN	0.0136	0.0023	0.0024	0.0038	0.0087
BK.JCC	40.8175	-124.0296	321.1	BK	HNN	0.1304	0.0200	0.0201	0.0251	0.0836
BK.JRSC	37.4037	-122.2387	88.0	BK	HNN	0.3231	0.3283	0.7434	0.3372	0.1502
BK.MCCM	38.1448	-122.8802	47.3	BK	HNN	1.6251	0.8413	1.8876	1.8527	0.8995
BK.MHC	37.3416	-121.6426	111.0	BK	HNN	0.2674	0.2041	0.4540	0.3453	0.0579
BK.MNRC	38.8787	-122.4428	71.1	BK	HNN	1.3056	0.8081	1.5676	1.3425	0.6179
BK.MOD	41.9025	-120.3029	440.6	BK	HHN	0.0295	0.0082	0.0087	0.0173	0.0121
BK.ORV	39.5545	-121.5004	161.1	BK	HNN	0.0981	0.0230	0.0507	0.0389	0.0261
BK.PACP	37.0080	-121.2870	159.2	BK	HNN	0.2576	0.1616	0.2943	0.2247	0.0597
BK.PKD	35.9452	-120.5416	294.7	BK	HHN	0.0746	0.0128	0.0193	0.0380	0.0188
BK.RAMR	35.6360	-120.8698	311.6	BK	HNN	0.1068	0.0383	0.0943	0.1161	0.0309
BK.RFSB	37.9161	-122.3361	30.9	BK	HNN	1.3779	1.7382	3.7026	2.3064	0.2488
BK.SAO	36.7640	-121.4472	176.0	BK	HNN	0.1338	0.0323	0.0564	0.1074	0.0310
BK.SCCB	37.2874	-121.8642	107.9	BK	HNN	0.5528	0.7395	2.3074	0.7961	0.0897
BK.SCZ	36.5980	-121.4030	194.4	BK	HHN	0.0937	0.0240	0.0387	0.0332	0.0116
BK.SUTB	39.2291	-121.7861	118.1	BK	HNN	0.3687	0.1789	0.4401	0.3556	0.1447
BK.TCHL	35.6881	-120.4009	325.8	BK	HNN	0.0788	0.0303	0.0872	0.0701	0.0391
BK.THIS	35.7240	-120.2284	330.6	BK	HHN	0.0833	0.0157	0.0336	0.0481	0.0212
BK.TRAM	35.6769	-120.2709	332.9	BK	HHN	0.0934	0.0192	0.0247	0.0823	0.0417
BK.TSCN	35.5440	-120.3481	342.0	BK	HNN	0.0824	0.0170	0.0270	0.0598	0.0312
BK.WDC	40.5799	-122.5411	260.1	BK	HHN	0.0364	0.0123	0.0217	0.0287	0.0122
BK.WENL	37.6221	-121.7570	79.4	BK	HNN	0.6962	0.4160	0.9172	1.1678	0.2218

Figure 2-14. ShakeMap Instrument Station List (Sample, NS Channel Only)

Each instrument can record three channels. Depending on instrument health, some instruments might not record in one or more channels, or have some other type of loss of data. Also, depending how the instruments were set up, the horizontal orthogonal directions might be NS and EW (true in nearly all instruments), but sometimes as channels 2 and 3 (90 degrees from each other). In SERA, the data for each channel is assessed, grouped into NS, EW or Vertical bins, and then listed accordingly; missing / bad data is listed as -1.0000 (for example, instrument BK.CVS) and this data is ignored when computing maps, as well as minima and maxima.

Figure 2-15 shows more of the NS channel instruments, highlighting two that have strong motions (68150 and 68310). Comparing the results from these two instruments (both near the epicenter):

- Both instruments show high PGA and PSA03 motions (epicentral distance varying by a factor of 2, and motions vary by about a factor of 2)

- Instrument 68150 also shows high PGV, PSA10 and PSA30 motions, but instrument 68310 shows only about 1/10th the motions at T = 1.0 seconds, or 1/20th the motions at T = 3.0 seconds. This suggests that instrument 68310 is a "rock" site, while 68510 is a "soil" site.

RAW STATIONLIST DATA FOLLOWS (First 2000 stations)

	STATION CODE	LONGITUDE decimal degrees	LATITUDE decimal degrees	EPICENTER DISTANCE km	NTWK CODE	CH NS 3	PGV cm/sec	PGA % g	PSA03 % g	PSA10 % g	PSA30 % g
	CE.58306	37.7625	-122.4556	49.4	CE	HNN	0.4950	1.0218	1.6919	0.5378	0.1577
	CE.58339	37.6971	-122.0802	58.6	CE	HNN	1.2710	1.0950	4.0486	2.3617	0.1702
	CE.58340	37.7152	-122.0277	58.4	CE	HNN	0.8460	1.3730	4.7284	1.1971	0.1232
	CE.58346	37.6799	-122.1259	59.2	CE	HNN	1.0760	1.0907	3.4363	1.1561	0.2227
	CE.58349	37.6950	-122.1118	58.0	CE	HNN	1.3280	1.2384	3.7862	1.5245	0.1894
	CE.58361	37.8952	-122.1526	35.8	CE	HNN	1.6290	2.6340	6.3403	2.0393	0.2969
	CE.58376	37.6233	-122.1303	65.2	CE	HNN	1.0570	0.8960	3.0340	1.0821	0.2747
	CE.58406	37.6260	-122.0502	66.9	CE	HNN	0.7320	0.9207	2.1967	1.2771	0.1007
	CE.58408	37.9608	-122.3422	26.0	CE	HNN	1.7920	1.6873	3.3089	3.6013	0.2477
	CE.58418	37.6252	-122.0920	65.9	CE	HNN	0.7950	0.9061	2.5391	1.3545	0.0963
	CE.58438	37.9299	-122.2996	29.3	CE	HNN	0.9560	1.2740	4.6684	1.4345	0.1944
	CE.58447	37.5251	-122.0999	76.5	CE	HNN	1.0080	1.2836	5.0308	1.2521	0.1064
	CE.58461	37.4243	-122.1780	86.2	CE	HNN	1.1800	1.9626	7.3625	0.9044	0.1442
	CE.58463	37.8097	-122.2806	42.7	CE	HNN	1.0270	1.1637	2.8290	1.4520	0.2557
	CE.58471	37.8761	-122.2505	35.6	CE	HNN	1.1940	1.3046	3.4338	1.7969	0.1962
	CE.58497	37.6750	-122.0300	62.5	CE	HNN	0.5620	0.7256	2.3417	0.5668	0.0792
	CE.58505	37.9355	-122.3434	28.8	CE	HNN	1.3900	1.6514	4.7784	2.1668	0.1954
	CE.58558	37.9783	-122.3298	24.0	CE	HNN	2.2890	2.3142	7.7324	4.3885	0.4299
	CE.58560	37.5849	-122.5081	69.7	CE	HNN	0.7620	1.6933	3.1664	0.5363	0.1082
	CE.58565	37.9694	-122.5243	30.5	CE	HNN	1.1880	2.2467	9.5992	0.6210	0.1360
	CE.58667	37.9730	-122.0360	33.6	CE		-1.0000	-1.0000	-1.0000	-1.0000	-1.0000
	CE.58790	37.8206	-122.2354	41.9	CE	HNN	0.8700	1.1894	3.4663	0.9704	0.0964
	CE.67266	38.0179	-121.7516	51.0	CE	HNN	0.8020	0.8616	1.9243	1.3795	0.2724
	CE.67557	38.0141	-121.8148	46.2	CE	HNN	2.0080	1.5989	2.7416	3.7912	0.4189
	CE.68034	38.5381	-122.2329	33.0	CE	HNN	1.6110	2.1534	4.2985	1.3121	0.7203
	CE.68035	38.9122	-122.7657	83.4	CE	HNN	1.1760	0.4358	0.8140	0.9484	0.4136
	CE.68045	38.2612	-122.0492	20.5	CE	HN3	2.9020	3.1248	10.6464	4.3760	0.0000
Soil	CE.68150	38.2704	-122.2774	4.0	CE	HNN	54.7680	33.5104	71.9754	52.5071	10.1190
	CE.68208	38.4972	-122.7604	46.7	CE	HNN	4.4970	2.7550	8.4821	7.4150	1.4345
Rock	CE.68310	38.1217	-122.2751	8.7	CE	HNN	5.4740	18.8071	34.0384	5.5431	0.4896
	CE.68323	38.0334	-122.1170	23.9	CE	HNN	1.4320	1.8280	6.2079	1.8569	0.2267
	CE.68326	38.4005	-122.8274	46.2	CE	HNN	2.7360	2.8923	5.1133	1.9118	2.5591
	CE.68327	38.4674	-122.6541	37.5	CE	HNN	8.3520	7.3598	18.9435	16.7943	1.5095
	CE.68328	38.4694	-122.7457	43.8	CE	HNN	3.9260	2.4394	7.3750	5.2332	3.2189
	CE.68329	38.4413	-122.7476	42.2	CE	HNN	4.4910	2.9967	5.2532	4.4760	2.2217
	CE.68367	38.0043	-122.2620	21.5	CE	HNN	3.8900	5.5911	20.7429	3.3414	0.4988
	CE.68433	38.0981	-122.5593	22.5	CE	HNN	2.7950	3.9396	10.9313	2.4092	0.2587
	CE.68440	38.3504	-122.8736	48.0	CE	HNN	1.0540	1.5271	3.0390	1.1771	0.3311
	CE.69039	38.3110	-123.0527	62.3	CE	HNN	1.9520	2.0197	4.4560	3.2239	0.3416
	CE.69044	38.5176	-123.2470	84.9	CE	HNN	0.9990	1.0599	1.8269	1.5820	0.2537
	CI.ADO	34.5505	-117.4339	594.5	CI	HHN	0.0134	-1.0000	0.0102	0.0111	0.0134
	CI.AGO	34.1465	-118.7670	550.4	CI	HHN	0.0043	0.0055	0.0043	0.0030	0.0033
	CI.ALP	34.6871	-118.2995	529.0	CI	HHN	0.0087	0.0042	0.0052	0.0086	0.0026
	CI.ARV	35.1269	-118.8301	460.3	CI	HHN	0.0051	0.0033	0.0090	0.0078	0.0025
	CI.BAC	33.6122	-117.0406	695.2	CI	HNN	0.0068	-1.0000	0.0012	0.0013	0.0016
	CI.BAK	35.3444	-119.1044	425.7	CI	HHN	0.0093	0.0042	0.0081	0.0065	0.0056
	CI.BBR	34.2623	-116.9207	650.5	CI	HHN	0.0035	0.0021	0.0028	0.0064	0.0015

Figure 2-15. ShakeMap (v2) Instrument Station List (NS Channel Only)

Figures 2-16 and 2-17 show the maximum recorded for each channel, for 655 (v3) or 619 (v2) stations. The highest recorded PGA = 0.9790 g (v3) (Time history in Figure 2-18).

Compare to the ShakeMap, where the inferred highest horizontal motion in the area is PGA = 0.8532 g (v3). As discussed earlier, the ShakeMap motions are different than the instrument motions due to the use of attenuation models, and various interpolation / soil computations, to backward infer the highest motions at the epicenter (fault rupture for v3). The estimated error at the instruments is likely under ±2%; the estimated error at the vast majority of the ShakeMap locations is at least ±50%. As the "grid" cell with the instrument that recorded 0.979g also has another nearby instrument that recorded much lower motions, the resulting ShakeMap (v3) averages out the very high 0.979g value to a lower value.

```
 There are   665 stations with good recordings. Limit to 2000 in SERA 8.4
------------------------------------------
 Maxima for Channel East-West --E --2
 PGV   =    86.8661 cm/sec
 PGA   =    51.7056 % g
 PSA03 =   117.2478 % g
 PGA10 =   102.0936 % g
 PSA30 =    19.0000 % g
------------------------------------------
 Maxima for Channel Vertical --Z
 PGV   =    45.4651 cm/sec
 PGA   =    31.5915 % g
 PSA03 =    56.8638 % g
 PGA10 =    33.7754 % g
 PSA30 =    19.1565 % g
------------------------------------------
 Maxima for Channel North South --N --3
 PGV   =    63.7525 cm/sec
 PGA   =    97.9024 % g
 PSA03 =   132.2048 % g
 PGA10 =    99.4780 % g
 PSA30 =    24.0784 % g
```

Figure 2-16. Instrument Maxima (v3)

```
There are   619 stations with good recordings. Limit to 2000 in SERA 8.4
-------------------------------------------
Maxima for Channel East-West --E --2
PGV   =    54.1489 cm/sec
PGA   =    37.6832 % g
PSA03 =   117.2478 % g
PGA10 =    57.2013 % g
PSA30 =     9.0000 % g
-------------------------------------------
Maxima for Channel Vertical --Z
PGV   =    14.7112 cm/sec
PGA   =    20.9926 % g
PSA03 =    39.1116 % g
PGA10 =    20.6679 % g
PSA30 =     5.9644 % g
-------------------------------------------
Maxima for Channel North South --N --3
PGV   =    54.7680 cm/sec
PGA   =    40.7344 % g
PSA03 =   107.8321 % g
PGA10 =    52.5071 % g
PSA30 =    16.0139 % g
```

Figure 2-17. Instrument Maxima (v2)

Figure 2-18 shows the time history for the NS-direction motion for instrument CE.68206. See Section 2.6 for further discussion of this instrument.

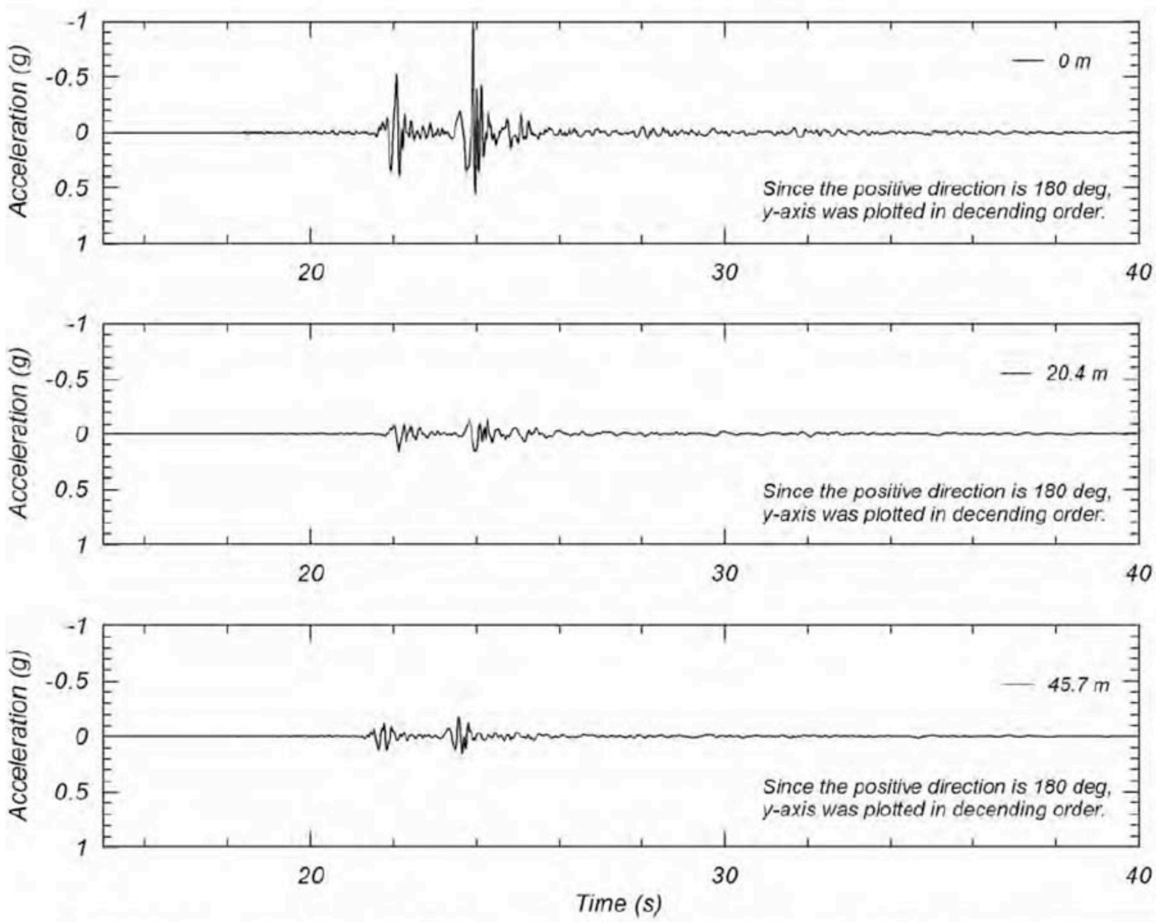


Figure 2-18. Instrument Time History (North-South Direction) (Carquinez Bridge)

2.4 Surface Faulting

Surface faulting occurred at many locations to the west of downtown Napa. Figure 2-19 shows a map that highlights the prior mapped locations of lineaments in the West Napa fault zone (yellow and blue lines) and field observations of surface faulting (red dots). This map shows information available to the USGS by August 26 2014 (2 days post-earthquake).

David Schwartz of the USGS reports that the locations of surface faulting (red dots in Figure 2-19) do not correspond closely to the prior mapped locations of the West Napa fault (yellow lines in Figure 2-19).

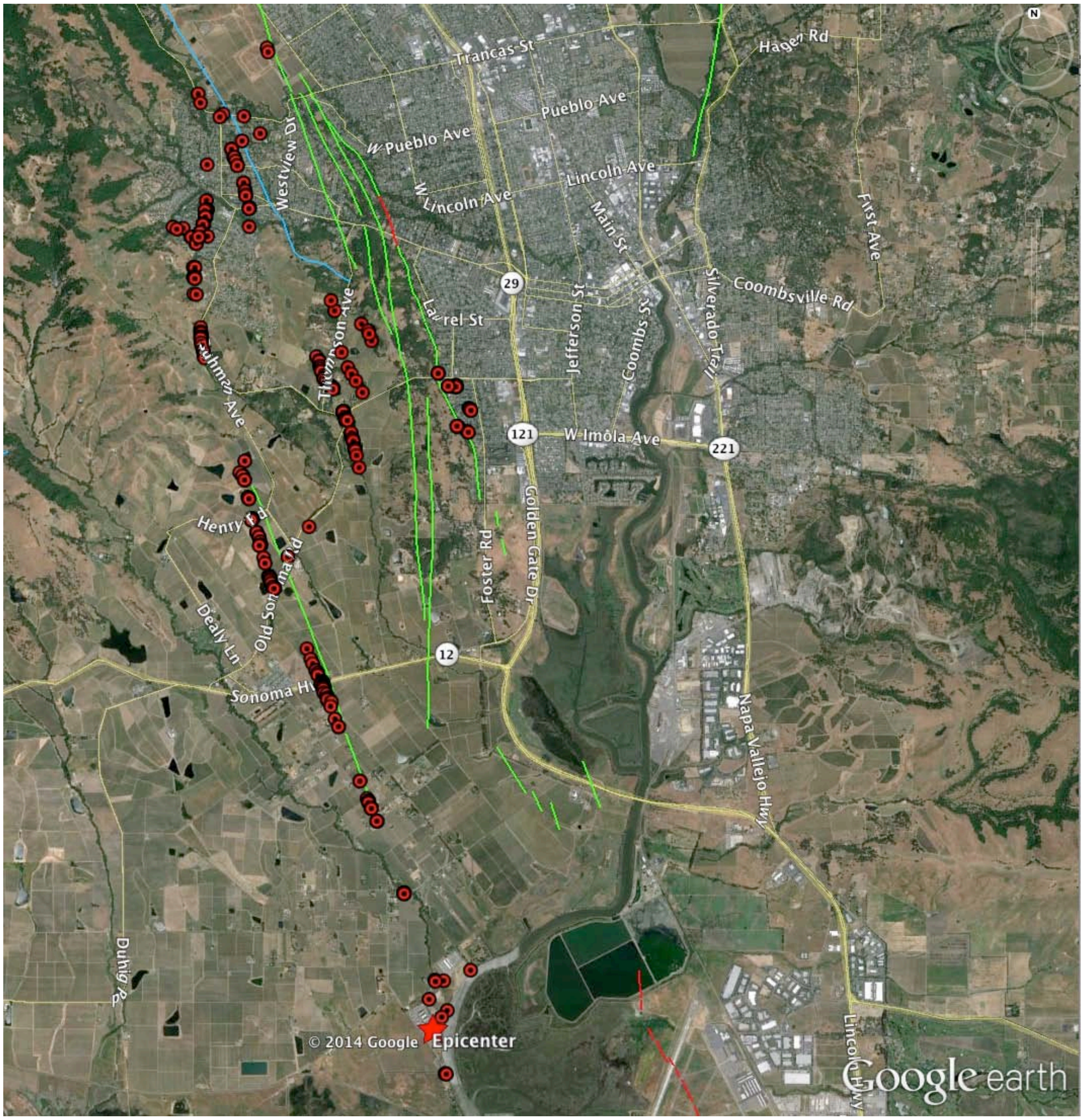


Figure 2-19. Map of Surface Faulting Observations (Red Dots)

Figures 2-20 and 2-21 show buckled sidewalks at two of the fault crossing locations (red dots in Figure 2-19). These figures show two of many such sidewalk buckles in the west part of Napa near Meadowbrook Drive. In this area, there were about 8 streets, running nearly perpendicular to the strike of the fault. At each street, there was commonly one or two sidewalk buckles (one each side of the street), and if one maps the location of the buckles, one gets a more-or-less straight line of red dots, as shown in the top left part of Figure 2-19. Inspecting these buckles, one observes that there was some right lateral movement, as well as possibly some thrusting movement at the surface, resulting in net compression in the sidewalk slabs. This compression then results in the uplift of two adjacent concrete slabs as seen in Figures 2-20 and 2-21. Underneath the ground, the ground movements are also applied to buried water pipes, wastewater sewers, and natural gas pipes, and the impacts on these buried lifelines will be described later in this report.

See the GEER report (2014) for a comprehensive list and locations of sidewalk buckles.

Figure 2-20. Buckled Sidewalk at Fault Offset Location

Figure 2-21. Buckled Sidewalk at Fault Offset Location

The location, extent and sense of faulting indicates the following:

- Prior mapped locations of the West Napa fault were sketchy.
- The length of fault zone is much longer than would be expected for a M 6.0 earthquake.
- The amount of offset measured (up to 40 cm, more commonly about 10 cm) is also higher than what would be expected for a M 6.0 earthquake.
- Prior to the earthquake, if a designer was to select the likely sense of fault offset at the surface, it would likely have been mostly assigned to be right lateral slip, with perhaps 10% to 15% of the right lateral slip movement being assigned to "up/down" movement. In some locations, this would have been a reasonable assumption for design. In other locations, this might have missed the thrust element of the offset, as evidenced in the sidewalk buckles in Figures 2-20 and 2-21. This suggests that for buried pipe design, it might be reasonable to assign at least some thrust movements for faults that have not been well characterized.
- Prior to this earthquake (and the Napa earthquake of 2000), some thought that the West Napa fault was active within the last 130,000 years. With two ruptures since 2000, the activity rate shows the fault is Holocene active.

On August 26, 2014, some of the authors visited an area which shows ground failure, located by the solid yellow line in Figure 2-22. In Figure 2-22, the dashed yellow line shows the inferred location of the Napa fault zone, based on prior studies. In one projects this dashed line to the north, where it would connected up with the mapped Browns Valley segment of the West Napa fault zone, it is located about 2 km easterly of the solid yellow line, where (apparently) surface rupture was observed at this location.

The nature of the cracks suggest surface faulting, for the following reasons:

- It seems to be right lateral in nature
- The ground cracks are en echelon, oriented in a manner consistent with soil pull apart associated with right-lateral faulting
- The cracks, if projected north-northwesterly as suggested by the direction of the solid yellow line in Figure 2-19, would go over the epicenter. If we assume the West Napa fault zone has a 90 degree dip (purely vertical), then the rupture would correspond to the presently-observed fault location.
- The site with these ground failures is mapped as not likely to liquefy, using the geologic maps (mapped at border of Qoa and pre-Quaternary soils). A Moderate-high liquefaction zone is mapped a few hundred west of this site (along a creek);

as the entire area is nearly flat, it would seem unlikely that there could be a lateral spread towards the creek.

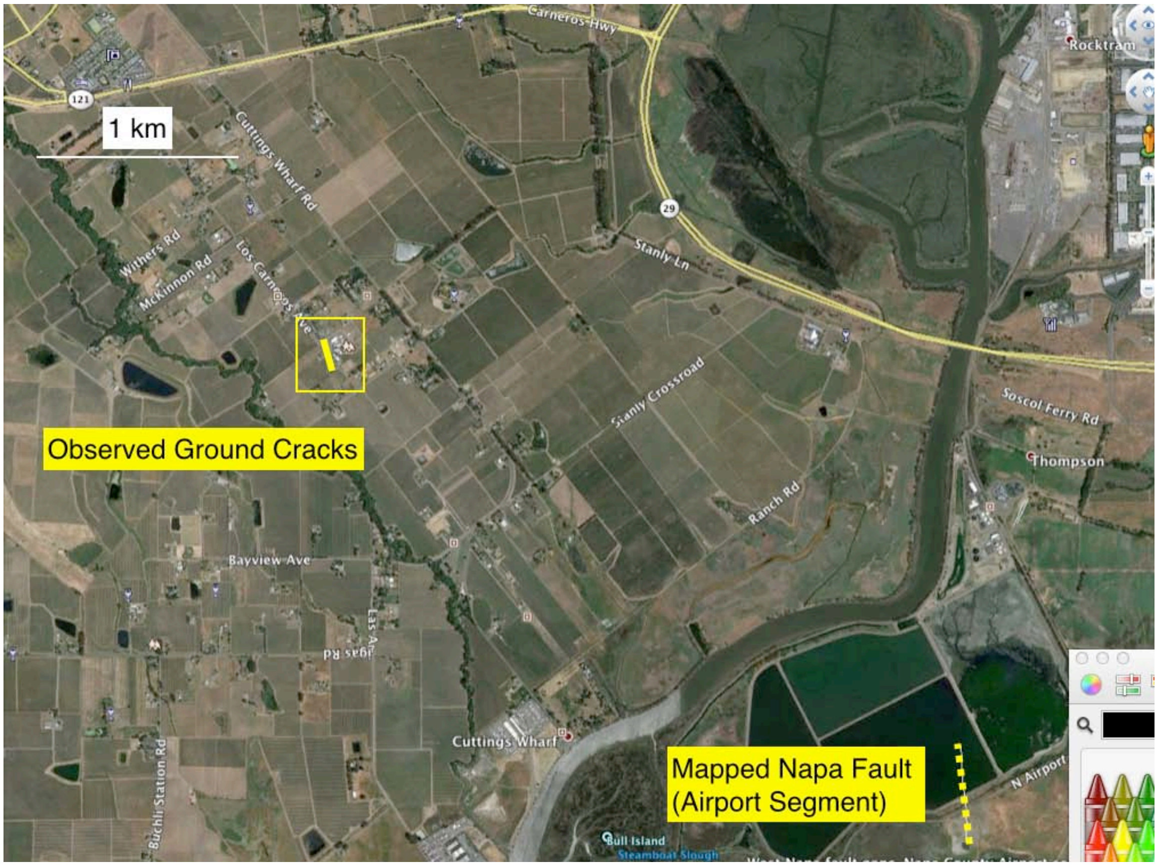


Figure 2-22. West Napa Fault Zone

Figure 2-23 shows a close up aerial view of the area in the highlighted box in Figure 2-22. In Figure 2-23, the thick dashed yellow line represents the zone with surface faulting. The property is a K – 8th grade school. The building noted "1958" building is one of the primary classroom buildings, and the oldest at the site.

We measured the width of the fault zone with observed ground failure at about 35 feet wide. The thick dashed line represents the strike of the faulting, but the actual cracks were en-echelon in nature, with most of the larger cracks oriented somewhat clockwise from the strike of the thick yellow dashed line. The cracks are very clear in the road (Los Carneros Avenue) and in the asphalt-paved parking lot of the school. To the west is a small "utilities building" housing switchgear (from the overhead PG&E distribution line along Los Carneros Avenue) as well as water quality equipment to treat water from the school's well.

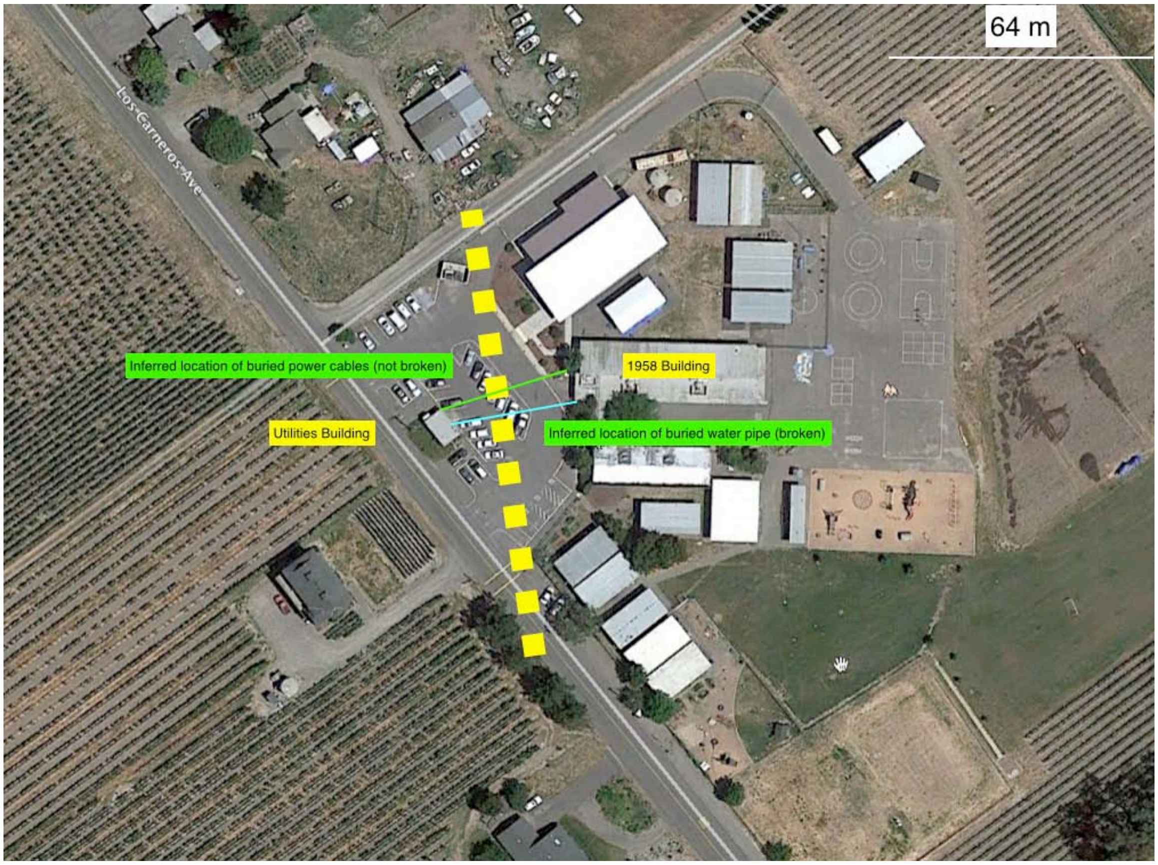


Figure 2-23. Aerial View of Fault Zone

Figure 2-24 shows Los Carneros Avenue (and John Eidinger), looking northerly, from a point just south of the fault offset zone. Photos taken around 4 pm local time, August 26 2014. Asphalt patches in the road pavement can be seen. To the west, the cracks in the ground are clearly seen on the westerly shoulder of the road. Note the overhead cable TV poles (west side of road) and overhead PG&E distribution poles (12 kV, east side of road).

Figure 2-24. Repaired cracks in street

Figure 2-25 shows the ground cracks that have been repaired by August 25 and some newly formed cracks (post-seismic "after-slip") (and Raymond Trinh).

Figure 2-25. Repaired and newly formed cracks in street

Figure 2-26 clearly shows the strike of the fault and the en echelon ground cracks. There appears to be about a 20° clockwise rotation of some of the en echelon cracks. One practical aspect is that for buried pipes crossing a fault, the fault offset might be along the strike, or perhaps rotation 20 to as much as 40 degrees or so (clockwise for right lateral, counterclockwise for left lateral).

Figure 2-26. Road cracks (repaired and new), looking northerly

Figure 2-27 shows the parking lot for the school, looking northerly. In the foreground, a crack (painted white after the earthquake to help identification) is seen, again oriented in en echelon clockwise direction as compared to the strike of the fault. In the center of the photo are several orange cones, surrounding where the water pipe (to-from well and the utility building on the left). The ejected sand at this locations is from the sand surrounding the water pipe, that was ejected as part of the pipe break (not from liquefaction).

Figure 2-27. Parking lot cracks, looking northerly

Figure 2-28 shows the largest crack in the parking lot, paring originally white, and then as the crack grew wider, orange. The ruler shows almost 4 inches of opening.

Figure 2-28. Parking lot crack, looking northerly

The power pole with (Figure 2-29), located on the street just west of the utilities building, shows no particular distress. The pole-mounted transformer does not look distressed and there were no signs of oil leak. The pot head / line drop looks undisturbed. According to the school's staff, the power was out on Sunday (August 24) morning. Once power was restored at this location, the line drop into the utilities building worked, and the underground cables from the utilities building into the school buildings worked. In other words, the cable (school-owned) that crossed the fault was not damaged to the point of becoming non-functional. In other earthquakes around the world, short (commonly shorter than 200 meter) secondary buried power cables have had a much lower failure rate due to modest PGDs (on the order of several inches) than long (several km) direct buried cables. This superior performance, all other factors being equal, is attributed to the available slack at either termination of the short cable, that can be used up at the specific PGD zone; whereas any available slack in a very long cable is "too far away" and the soil can effectively anchors the cable preventing any available slack from being used at the PGD zone where it is needed. This analogy would have to be adjusted if the buried cable is within ducts (PVC or Transite are common) rather than in direct burial.

Figure 2-29. Power Pole, adjacent to fault zone (left side looking north, right side looking south)

2.5 How Accurate Are ShakeMaps

As discussed in Section 2.3, the USGS prepared and released four versions of ShakeMaps for this earthquake. In the initial two releases, the ShakeMaps used about 600 instruments, plus the epicentral location, to produce maps, such as Figure 2-5. As can be seen in Figure 2-5, the assumption of a epicenter, rather than a ruptured fault, gives these maps a strong "bulls-eye" variation in the ground motions. While a "bulls-eye" shape might be reasonable for magnitude 5 and below, once the magnitude of the earthquake is large enough, the length of actual rupture will tend to produce a more "oblong" type shaking map, such as in Figure 2-2b.

Comparing the maps in Figures 2-2a,b (with fault rupture shape incorporated into the ShakeMap) and 2-5 (ShakeMap developed relying on epicentral location), there are huge differences, commonly -50% to +100%. In areas toward Vallejo and south of the Carquinez Strait, the version 4 ShakeMap (Figure 2-2b) is more than 100% higher than the version 2 ShakeMap (Figure 2-5).

As the version 4 ShakeMap includes the fault rupture and about 100 more instruments (about 700 total) as compared to the version 2 ShakeMap, the USGS informs the public that the version 4 ShakeMap is "more accurate" and with less "variability". On the surface, this seems reasonable, as uncertainties such as distance to fault rupture have been removed, and there are more instruments with real recordings. But in this particular situation, the high levels of motion toward the south of the rupture are greatly influenced by two instruments, both located next to the southern approach of the Carquinez bridge. These instruments are included in the later ShakeMaps (version 3 and 4) and influence the southern portions of the strong shaking parts of the maps. Figure 2-30 and 2-31 show the housings of these two instruments.

- Figure 2-30. This photo shows the instrument CE.68259 with the Carquinez bridge in the background. The photo is taken looking northwards, and the new Carquinez bridge (suspension bridge designed by Mark Ketchum) is on the left, and the older Carquinez bridge (cantilever truss type) is on the right.

- Figure 2-31. This photo shows instrument CE.68026, and Charles Scawthorn (left) and John Eidinger (right). The large reinforced concrete piers of the older highway bridge are in the immediate background. These piers are very tall, and support the bridge. The distance of the piers to the instrument is similar to the distance from the ground to the bridge deck.

Figure 2-30. Instrument with New (Left) and Old (Right) Carquinez Bridges in Background

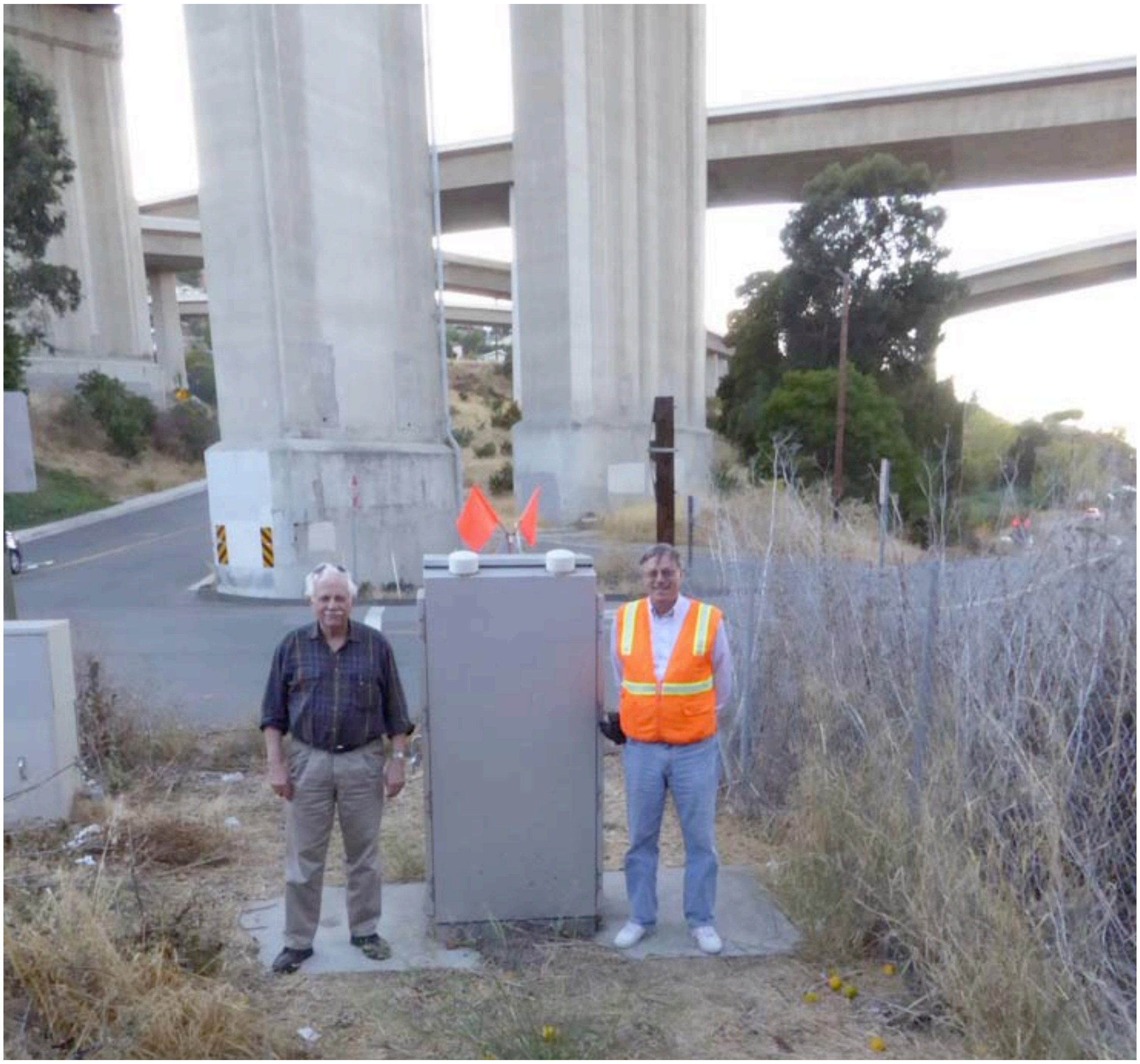


Figure 2-31. Instrument under old Carquinez Bridge with Scawthorn (left) and Eidinger (right)

Table 2-1 compares the peak recordings from these two instruments.

Item (Damping in %)	CE.68206	CE.68259
Latitude	38.0540	38.0548
Longitude	-122.2250	-122.2264
Figure	Figure 2-31	Figure 2-30
Distance to Epicenter (km)	20.0	19.9
PGA (NS) g	0.979 g	0.424 g
PGV (NS) cm/sec	22.2 cm/sec	19.8 cm/sec
SA (NS 0.3 sec, 5%) g	1.322 g	0.948 g
SA (NS 1.0 sec, 5%)	0.082 g	0.102 g
SA (NS 3.0 sec, 5%)	0.010 g	0.012 g
PGA (EW) g	0.517 g	0.177 g
PGV (EW) cm/sec	10.4 cm/sec	11.0 cm/sec
SA (EW 0.3 sec, 5%) g	0.432 g	0.323 g
SA (EW 1.0 sec, 5%)	0.115 g	0.122 g
SA (EW 3.0 sec, 5%)	0.010 g	< 0.01 g
PGA (V) g	0.316 g	0.172 g
PGV (V) cm/sec	7.42 cm/sec	6.33 cm/sec
SA (V 0.3 sec, 5%) g	0.518 g	0.360 g
SA (V 1.0 sec, 5%)	0.236 g	0.045 g
SA (V 3.0 sec, 5%)	0.003 g	0.004 g

Table 2-1. Instrument Recordings

Maximum NS and EW Motions. USGS's ShakeMap software uses the maximum of the NS and EW motions. Often, these motions are ±20% of each other. In this case, the motions are +90% (PGA) or +306% (SA at T = 0.3 seconds). These are large differences. If one is using the ShakeMaps for post-earthquake loss estimates, one has to wonder if the decision to present the maximum of NS and EW motions is suitable. By using the instrument data directly, de-aggregating the directional data as suitable for the evaluation at hand, rather than the single value in the ShakeMap, improved loss estimates can be made.

Are these instruments Free Field? USGS assumes that these instruments are Free Field instruments, meaning that their recordings are not materially influenced by nearby structures. Examining Figures 2-30 and 2-31, this assumption is likely not valid. The massive bridge supports are very close to the instruments. As the bridges moved in the earthquake, they would impart into the ground very high reaction forces. It is possible that during the earthquake, that hinge-type connections in the bridges opened / closed, or similar phenomena, leading to some high frequency shocks. The very high recorded motions at PGA / SA (T=0.3sec) are not reflected in the longer periods. This suggests that some type of "impact" forces in the bridge foundations are what the instruments are recording, and not the true free field motion. Further, if one uses commonly accepted attenuation models, the median PGA levels at these two instrument sites should have been about 0.1g or so; whereas one instrument recorded 0.97g (nearly 10 times higher than median expected). If one assumes sigma (total ground motion) of about 0.4 for PGA, then dispersion the 0.97g value is 5.7 standard deviations above the median. There is very little chance that this could have happened due to normal variations in free field ground motions.

Spatial variation. The two instruments in Table 2-1 are within 100 meters of each other, and both are located on "stiff soil over rock" type conditions. At the PGA level, the differences in motions are 130% (NS) and 292% (EW) and 182% (Vertical). At longer periods, the differences are lower. When processing the instruments, since both these instruments are located within a single ShakeMap "grid cell", ShakeMap averages the motions. If, the "gridding" of the ShakeMap had put these two instruments into two separate cells, the un-averaged data would have been used. So, by the arbitrary gridding process, the values assigned to the grid(s) for these instruments could have been vastly different. In either case, the gridded value is used in an interpolation scheme to influence the motions in nearby grids, although as one gets further away from these instruments, the influence of attenuation functions should outweigh the interpolation from recorded motion function.

Given these issues, discussions with former USGS staff, once the version 3 ShakeMap was produced, concluded that these two instruments (and especially CE.68026) should have been excluded from the production of future ShakeMaps. However, the version 4 ShakeMap (and latest version as of writing of this report) still contains these instruments.

Therefore, the PGA ShakeMap in Figure 2-2b is almost certainly much too high in the areas around Vallejo and points south.

It is recommended that future versions of ShakeMaps for important earthquakes (M 6 and larger near population centers) be peer reviewed, and anomalous instruments be removed from the production of the ShakeMaps.

Even without these two anomalous instruments, the variability in the produced ShakeMap should be considered at best ±50% in areas more than 300 meters from an instrument. The "binning" of NS and EW motions in ShakeMaps also introduces another error term that can be in the range of ±25% from the geometric mean of horizontal ground motions that are computed using modern GMPEs.

Further, while conceptually ShakeMaps should produce the same motion as actually recorded, at least at locations with instrumental recordings, the gridding process inherent in ShakeMaps can eliminate this accuracy. The built-in assumptions of soil type (Vs30) at each ShakeMap grid cell may not be correct, and certainly cannot be correct for cells that contain both hilly (and rock-like) conditions as well as valley (and soil-like) conditions. In the past few years, ShakeMaps have included routines to interpolate between "intensity" and "did you feel it" observations and instrumental hazard recordings (like PGA, PGV, etc.), which can further distort and mask the meaning of a map. For assessment of lifeline performance, one hopes to correlate observed damage (or good performance) to hazard parameters like PGA or PGV, etc., and not indirect "did you feel it" parameters.

Given these issues, it would be recommended that users of ShakeMaps account for the following:

- Automated (non peer reviewed) ShakeMaps produced by the USGS. Assume the standard error term on ground motion (intra-event type) of 0.6 to 0.8 for M 6 and larger; and 0.5 to 0.7 for M 5 and smaller. This should factor in the additional "noise" introduced by the gridding process, use of non-free field instruments, incorrect assumptions about soil conditions at each cell.

- Peer reviewed ShakeMaps produced by the USGS. In this process, instruments with anomalous recordings should be removed, and for M 6+ earthquakes, fault geometry should be included in the ShakeMap. Assume the standard error term on ground motion (intra-event type) of 0.4 to 0.6 for M 6 and larger for any grid that does not include an instrument; and lower by about 0.1 for grids that include an instrument; and lower to 0 at sites that exactly match the location (and site condition) of actual recordings where the grid value is the same as the recorded motion.

- For more accurate ShakeMaps, users can create ShakeMaps by taking the actual instrumental recordings; adding in instruments that the user might have access to, but the USGS does not; removing instruments that are judged to be anomalous; account for each instrument's actual site conditions; adjusting the forecast motions for actual site conditions at specific sites; and de-aggregating the motions for NS, EW and Vertical directions.

- Within the ShakeMap software, a variety of interpolation schemes are used, intending to minimize errors. As a by-product of the map making process, a "uncertainty map grid" could be produced, with a one-to-one correspondence with the grid.xyz file, to present the computed error term(s) for each grid cell. This will help end users make better forecasts of expected losses, as well as ranges (say plus or minus one standard deviation), and perhaps make better choices about where to deploy early assessment response for critical / sensitive facilities.

3.0 Performance of PG&E Power System

Nearly 70,000 PG&E customers experienced one or more power outages during this earthquake. Figure 3-1 shows the power outage time chart.

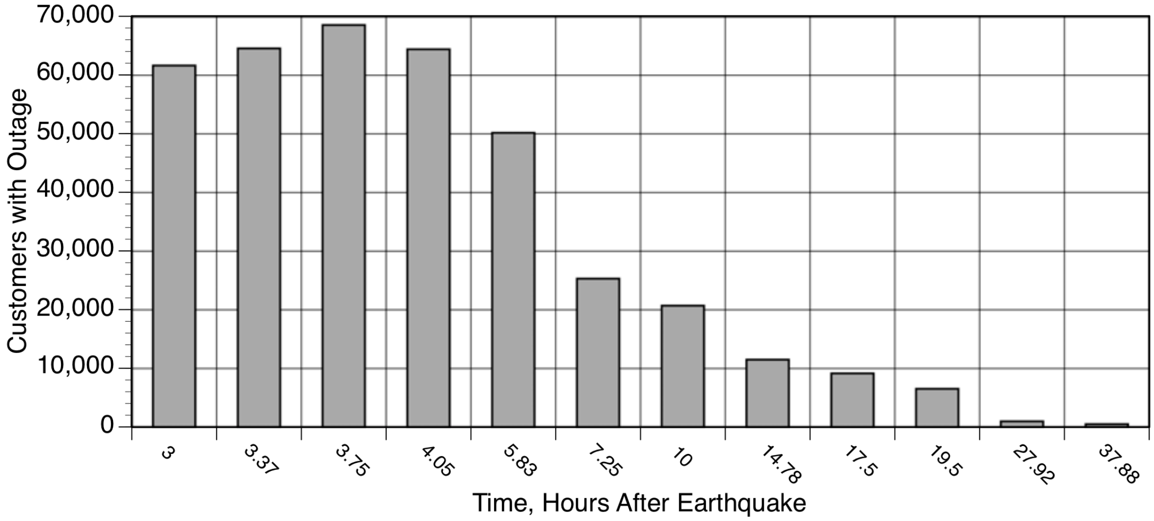


Figure 3-1. Power Outages

Within about 14 hours after the earthquake, PG&E had inspected 35 distribution and transmission substations. Initial observations indicated that oil leaked from some power transformer radiators; oil alarms occurred due to oil sloshing within the transformers (these were reset), some damage to scaffolding (no impact on equipment); a circuit breaker tripped and reclosed and remain closed.

On August 26, 2014, six substations were inspected by Anshel Schiff and John Eidinger. About 1,000 pieces of 60 kV to 230 kV voltage equipment and buildings were reviewed, all having been exposed to PGAs between 0.16g and 0.35g. The following summarizes key observations.

- Buildings. One precast concrete building suffered slight damage to the roof diaphragm. The building remained operational.

- Power transformers. 2 power transformers (installed pre-1980) had minor leaks of oil from radiators. Some of this leakage might have been pre-earthquake. The affected radiators were very flexible (first mode frequency from 2 to 3 hertz). All newly installed transformers had much stiffer radiators and no leaks. There was no damage to bushings (all porcelain) or surge arrestors (some porcelain, some composite).

- Circuit breakers, disconnect switches, circuit switchers. Nearly every component installed post-1990, with all 230 kV equipment having been seismically qualified to IEEE 693 (high seismic zone). No damage.

Figure 3-2 shows a 1977-vintage power transformer, with Prof Anshel Schiff in the foreground.

Figure 3-2. Power Transformer

Figure 3-3 shows the time history of response of the radiator. The forced vibration response is seen on the left (increasing blue line) and the free vibration response is shown on the right (two lines, with the blue line being the recorded motion, and the second line being a fitted sine wave motion attempting to match the response). From the matched sine wave, the best-fit first mode frequency is 2.905 hertz with 0.3% damping.

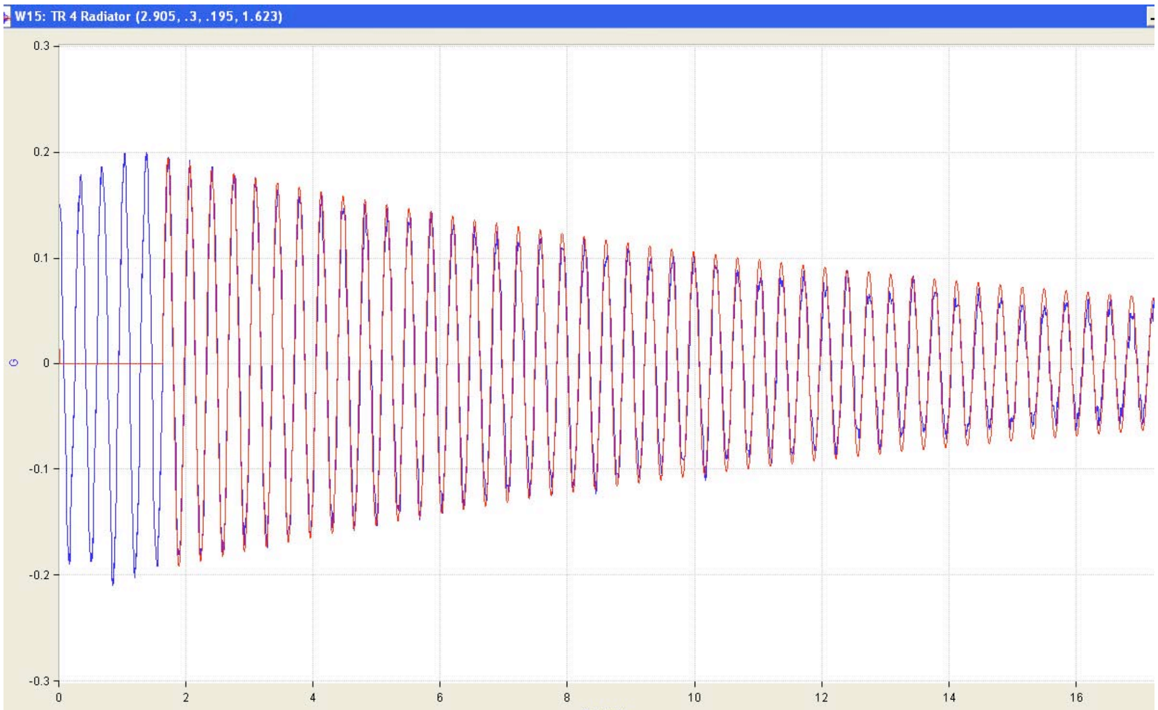


Figure 3-3. In Situ Test Vibration Response of Radiator (A. Schiff)

There was evidence of oil leakage at this transformer, Figure 3-4.

Figure 3-4. Transformer Oil Leak

Power outages were mostly due to damage within the distribution system (generally 12 kV).

The distribution system in the Napa area includes both overhead and buried feeders. Within the PGA > 0.15g zone (urban Napa and American Canyon), the estimated number of overhead structures (nearly all wood poles) is about 11,000.

In Figure 3-1, the time of maximum number of customers without power is about 3.75 hours after the earthquake, peaking at just under 70,000 customers. System wide, PG&E has about 5,100,000 customers, serving about 15,000,000 people. So, at the peak, about 1.4% of PG&E customers lost power. Of the customers who lost power, more than 99% had power restored within 24 hours.

Over the course of the first 24 hours, there were many aftershocks, typically in the M 3 range or so. While the level of shaking was low from these aftershocks, these aftershocks seem to have caused a few more outages.

The following summarizes the causes of the outages.

- 166 overhead, 3 underground
- 52 fuse related
- 41 wire related
- 10 equipment related
- 6 pole / cross arm / insulator related.

Using data collected from a different method, the following is the recorded damage in the distribution system:

- 63 spans of conductor damaged
- 12 transformers
- 15 cross arms
- 43 other items (e.g. insulators)
- No underground damage.

There are two common measures for power outages used by electric power utilities. These are:

- CAIDI (Customer Average Interruption Duration Index)
- SAIDI (System Average Interruption Duration Index)

$$CAIDI = \frac{\sum U_i N_i}{\sum \lambda_i N_i}$$

$$SAIDI = \frac{\sum U_i N_i}{N_T}$$

where

- U_i is the annual outage time for location i, (but in case of the earthquake, the outage time during the first day post-earthquake)
- N_i is the number of customers for location i (one customer is one meter)
- N_T is the total number of customers served
- Lambda(i) is the failure rate
- The numerator is the total number of customer-minutes of outage
- CAIDI is measured in units of time, often minutes or hours. It is usually measured over the course of a year. According to IEEE Standard 1366-1998, the median value for North American Utilities is about 1.36 hours of outages per year.
- SAIDI is measured in units of time, often minutes or hours. It is usually measured over the course of a year. According to IEEE Standard 1366-1998, the median value for North American Utilities is about 1.50 hours.

PG&E data suggests the following further statistics:

- 28 wires down in the distribution system (12 kV and some 21 kV)
- Phase to phase contact (wire slap) was the most common reason for outages.
- 76,040 customers were out of power at the peak time. The outages in Figure 3-1 were obtained as specified times post-earthquake, and it might be that some time about 3 to 5 hours post earthquake that there were modestly higher counts than those listed in Figure 3-1).
- 99% of customers were restored within 26 hours.

- Data collected by the CPUC shows that SAIDI was 5.5 minutes, and CAIDI was 315.2 minutes. The California Public Utilities Commission (CPUC) reports that CAIDI < 570 minutes (per "major outage") is good performance.

- While SAIDI of 5.5 minutes is modest, this value is based on Nt, presumed to be PG&E's system wide total. If one assumes that Nt in the affected area is closer to about 200,000, then the average outage duration in the affected areas was on the order of 60 times this value, or perhaps 330 minutes (5.5 hours). This corresponds reasonably well with the data in Figure 3-1, as well as CPUC's reported value of 315.2 minutes.

CPUC General Order 166 establishes standards for operation, reliability and safety during emergencies and disasters. One of the goals in General Order 166 is CAIDI of under 570 minutes. This requirement becomes effective if a utility experiences a major event. General Order 166 defines a "major outage" as occurring when "10 percent of the electric utility's serviceable customers experience simultaneous, non-momentary interruption of service". For the South NAPA earthquake, perhaps 200,000 people were affected, representing about 1.3% of the ~15,000,000 population served by PG&E.

4.0 Performance of Water and Sewer Systems

There are several moderate to large size water and sewer systems located in the areas with shaking of PGA over 0.10g:

- City of NApa. Largest water distribution system. Covered in Section 4.1.
- American Canyon.
- City of Vallejo.
- City of Sonoma Valley.
- Small Rural Water System near Epicenter.
- Department of Water Resources North Bay Aqueduct.

4.1 City of Napa Water System

The City of Napa was incorporated in 1872. Figure 4-1 shows that the City's water service area contains three boundaries:

- Designated water service area, which includes most of lower Napa Valley and the city of Napa (blue line),
- Rural Urban Limit line (RUL) (orange line).
- City limits (red line, nearly the same as the orange line).

The majority of potable water delivery is within the RUL (orange line). Outside the RUL, some potable water is delivered to the Monticello / Silverado community, the Congress Valley Water District and to agricultural customers along the Conn Transmission Main.

The City also exports water to the Cities of American Canyon (daily), St. Helena (daily), Calistoga (daily), Yountville (rare) and the California Veterans Home (rare). By "daily", it is meant that this is normally done. By "rare" , it is meant that the infrastructure is in place to deliver water, but those communities have separate water supplies that are used normally.

Water demand peaks at about 25 MGD during a hot spell in July and drops to about 7 MGD during the winter months. Landscape irrigation represents about half of yearly water demand. All potable water is provided from three surface water sources; no ground water is used. Of the total demand, about 53% is single family residential, 16% is multi-family residential, commercial is about 15%, institutional about 7%, landscape about 5%, St. Helena about 2%, agricultural about 1%, construction about 0.3%.

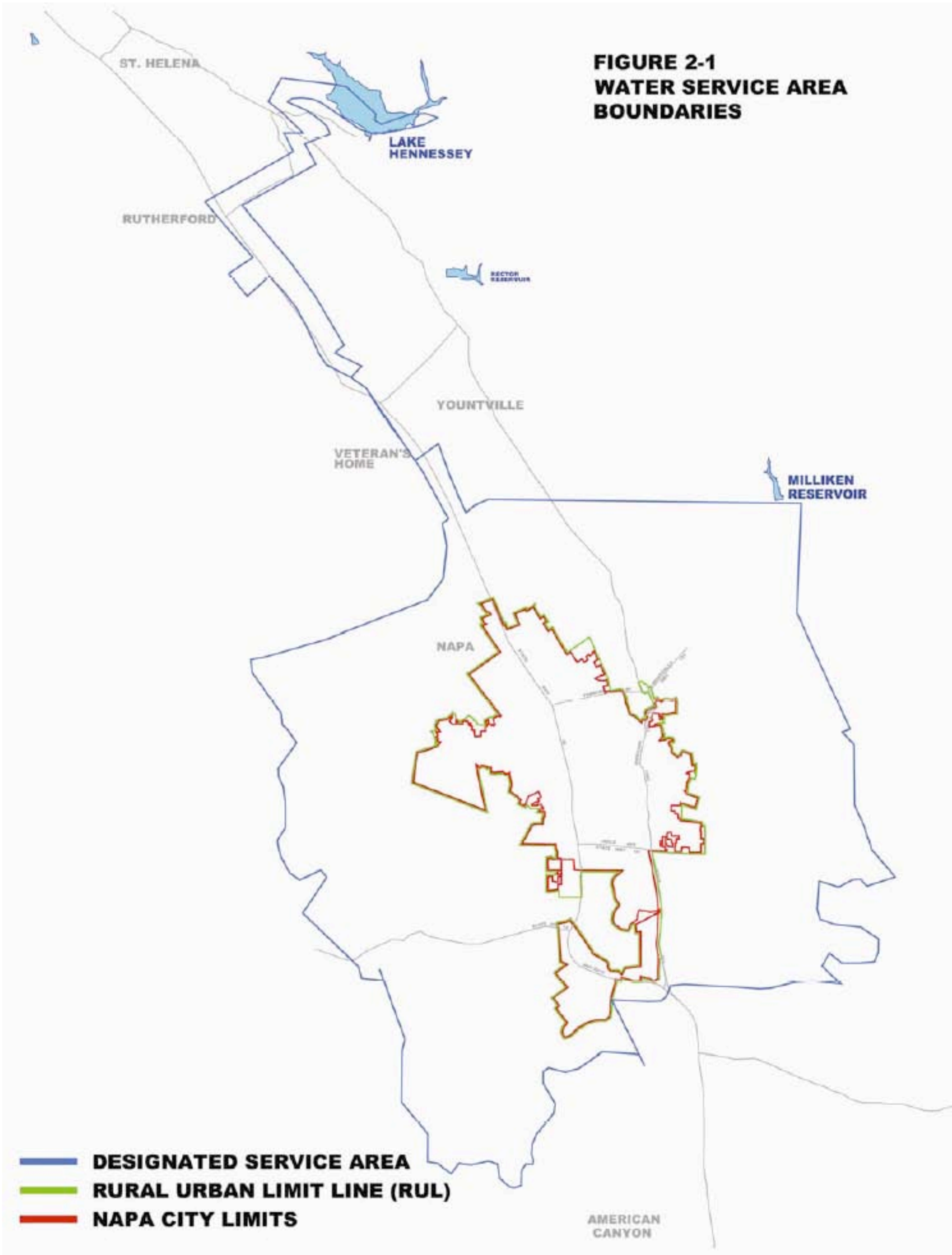


Figure 4-1. Napa Water System Service Area

Figure 4-2 shows the locations of the three water treatment plants serving Napa, as well as the major transmission pipelines in the water system.

- Lake Hennessey. Located about 14 miles north of the City if Napa water system. The lake was created by building Conn Dam in 1946. The Hennessey WTP began operations in 1981, with nominal treatment capacity of 20 MGD. PGA from this earthquake was about 0.1g. Facilities includes a circular concrete intake tower, flash mixing, coagulation, flocculation, sedimentation, filtration and disinfection. Treated water is stored in a buried 5.0 million gallon concrete clearwell tank on site. This treated water is delivered to the distribution system via a steel pipeline, 36-inch diameter Conn Transmission Main, about 20 miles long. This transmission pipeline suffered no damage.

- Milliken WTP. Prior to 1946, this was Napa's sole water supply. Milliken Dam was built about 1923. Normally, this WTP is used only during summer months. The storage capacity of the reservoir is limited due to seismic stability concerns of the dam. Raw water is diverted from Milliken Creek about 2 miles downstream of the dam, to the WTP, via a one-mile-long 16-inch diameter above ground raw water pipe. The current WTP was built in 1976, with a capacity of 4 MGD. It is a direct filtration plant, with a contract/reaction tank and four horizontal filters. Treated water is stored in a 2.0 million gallons clearwell tank. Water from the clearwell tank is delivered to the distribution system via the 3-mile-long Milliken Transmission Line. PGA about 0.15g. Milliken did not come on-line in response to the earthquake.

- Jamieson Canyon. PGA about 0.15 – 0.20g. Raw water for this WTP comes via the State Water Project's North Bay Aqueduct. The SWP diverts water from the Sacramento-San Joaquin Delta at Barker Slough pumping plant east of Fairfield (PGA < 0.05g) and the NBA moves the water about 21 miles westward to Cordelia Forebay; from there, the SWP water is pumped an additional 6 miles to two NBA terminal 5 MG reservoirs (built 2008) located at the WTP. The WTP provides potable water to the cities of Napa, Calistoga and American Canyon. Raw water from the WTP can also serve agricultural customers in American Canyon. Facilities includes a 5 MG tank. The WTP was originally constructed in 1968, expanded to 12 MGD in 1988, and expanded again in 2011 to 20 MGD. The WTP includes pre-and intermediate-ozonation, as well as rapid mixing, flocculation, sedimentation with tube settlers, gravity filtration, and disinfection. There is a 5 MG clearwell. The 42-inch diameter Jamieson Transmission Line delivers potable water to the City, splitting into 36-inch diameter and 24-inch diameter lines near the intersection of Highway 29 and 221. After this split, the west-side transmission pipeline is a rubber gasketed asbestos cement pipe; this pipe did not fail in the first week after the earthquake; but did suffer 3 leaks during the months afterward.

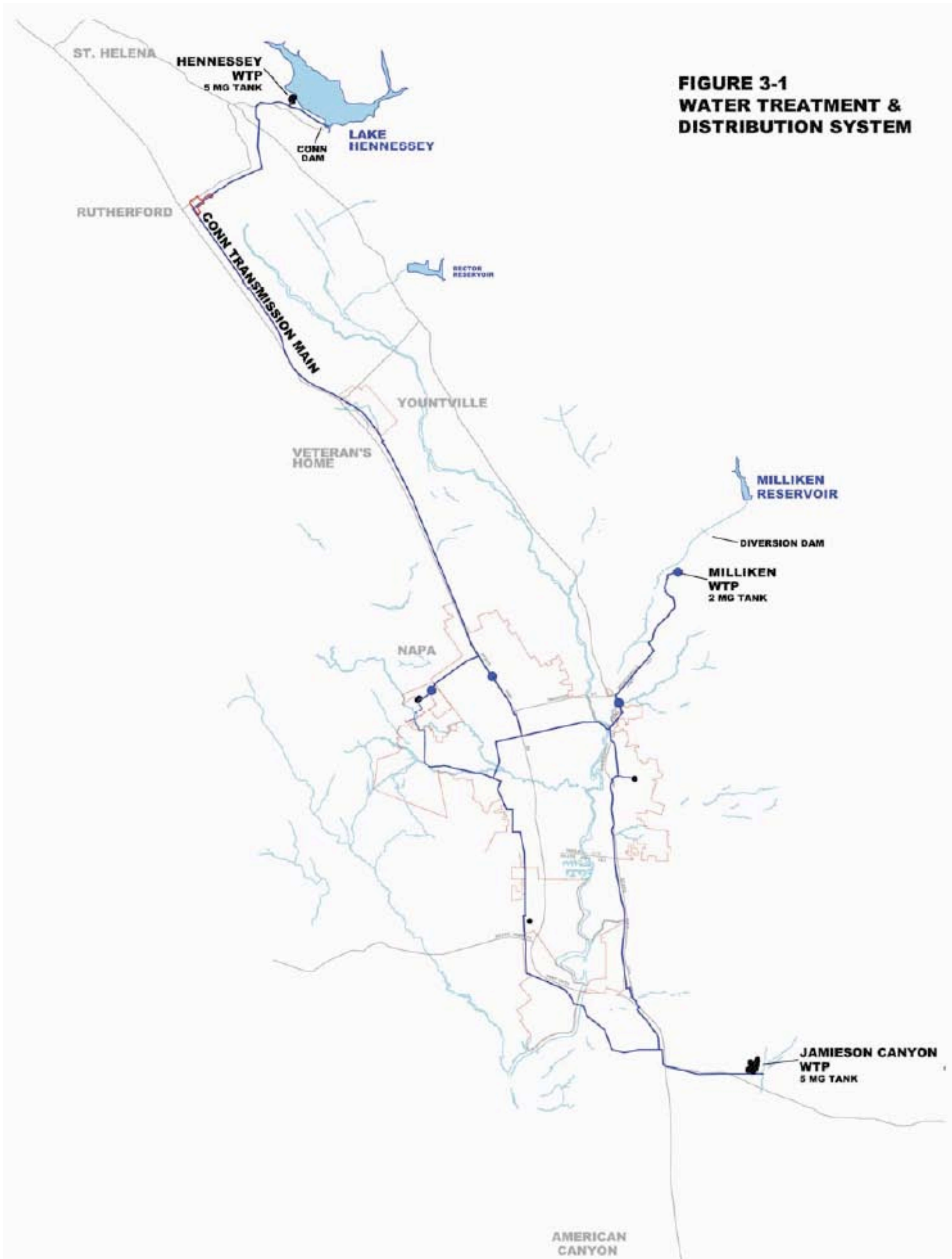


Figure 4-2. Napa Water System Major Pipelines and Location of Water Treatment Plants

Figure 4-3 shows the Lake Hennesey WTP.

Figure 4-3. Lake Hennessey Water Treatment Plant (38.4889, -122.3881)

Figure 4-4 shows the Jamieson WTP.

Figure 4-4. Jamieson Water Treatment Plant (38.2236, -122.2249)

The Napa Water Department (NWD) serves a population of about 84,000 people, via 25,000 services. NWD has 51 employees. The water system includes 3 water treatment plants, about 380 miles of pipe, 12 storage tanks with a total of 30 million gallon storage, 9 pump stations, 14 pressure regulating stations and is operated in 5 pressure zones. The 9 pump stations serve about 10% of the population; and about 90% of the populations is served by gravity flow coming from the water treatment plants.

As of September 30, 2014, Napa reported about 172 water pipe repairs. Through November 15, 2014, Napa reported 185 pipe repairs. Through February 2015, Napa reported 240 pipe repairs.

Table 4-1 lists the lengths of water pipes in the Napa water system (2012 data). Napa reports that in a typical year, there are about 80 to 100 pipe leaks in the city, system wide (about 0.21 to 0.26 repairs per mile per year). This leak rate for water pipes is consistent with U.S. industry average (about 0.24 to 0.27 leaks per mile per year). Even so, other water departments in California with primarily cast iron pipe of similar vintages as in Napa (but with non-aggressive soils) have system wide leak rates on the order of 0.06 leaks per mile per year. While detailed study of the historical incidence of pipe leaks and the pipe breaks in the 2014 earthquake remain to be done, to assess the correlation, a tentative finding is that the rate of water pipe damage in earthquakes will tend to be relatively high, if the historical leak rate is also high.

Age (years)	PVC	DI	CI	AC	RCCP	STL	Total	Pct of Total
< 20	6,600	225,600				100	232,300	13%
20-40	24300	370,500	83,400	14,100		100	492,400	28%
40-60		12,300	466,700	167,200	9,900	59,800	715,900	40%
60-80			173,100			100,400	273,500	15%
80-100			55,100				55,100	3%
> 100			10,300				10,300	1%
Total	30,900	608,400	788,500	181,300	9,900	160,400	1,779,500	100%
	2%	34%	44%	10%	1%	9%	100%	

Table 4-1. Length of Water Pipe Mains – Napa (Feet)

Table 4-2 lists the number of repairs by pipe material.

Material	Repairs	% Repairs	% Pipe	Repair per Mile
AC	8	5%	10%	0.23
PVC	2	1%	2%	0.34
CI	123	75%	44%	0.82
DI	18	11%	34%	0.16
Steel	3	2%	9%	0.10
Other / unk	7	4%		
Total	163	100%		

Table 4-2. Repair Rates for Water Pipe

An initial review of Table 4-2 shows that cast iron is the most vulnerable of pipe materials, with AC, PVC, DI and Steel all performing much better than Cast Iron. Further examination of the repairs to correlate against location (in terms of PGV and PGD) and age (especially with respect to corrosion) may yield additional insight. However, initial review suggest that that the overall repair rates of nearly 1.3 per km for cast iron pipe, and values between 0.16 and 0.5 repairs per km for other pipe materials) strongly suggest that area was impacted by high ground strains, some level of PGDs, possibly aggravated by highly corrosive soils and/or movement of concrete anchor blocks, etc. It is possible that seismic wave propagation speeds in areas underlain by soft clays may have led to exceptionally high ground strains.

With a total of 337 miles of pipe, if one adopts an industry-wide leak rate of about 0.2 leaks / mile / year, one would forecast a long term rate of about 0.2 * 337 = 67 leaks per year. For the period from September 30 to November 15 2014 (6 weeks), there were 13 additional leaks that needed repair. For the period from August 24 (day of the earthquake) through early February 2015, there were a total of 240 pipe repairs.

This higher leak repair rate in the months following an earthquake is not unusual, reflecting that many pipes were highly stressed / deflected by the earthquake (but not immediately broken), but over time, these highly loaded pipes fail at a higher rate than normal. One would expect that the long term pipe repair rate will decrease over time; the City of Napa confirmed this to be the case, in that by about mid January 2015, the leak rate seemed to have reduced to about the long term rate.

Figure 4-5 shows an overlay of pipe repairs (blue symbols) with the pre-earthquake location of mapped faults (red lines), along with zones subjected to surface faulting (black elongated zones). This map shows the pipe repair count as of September 2014, when it was 160.

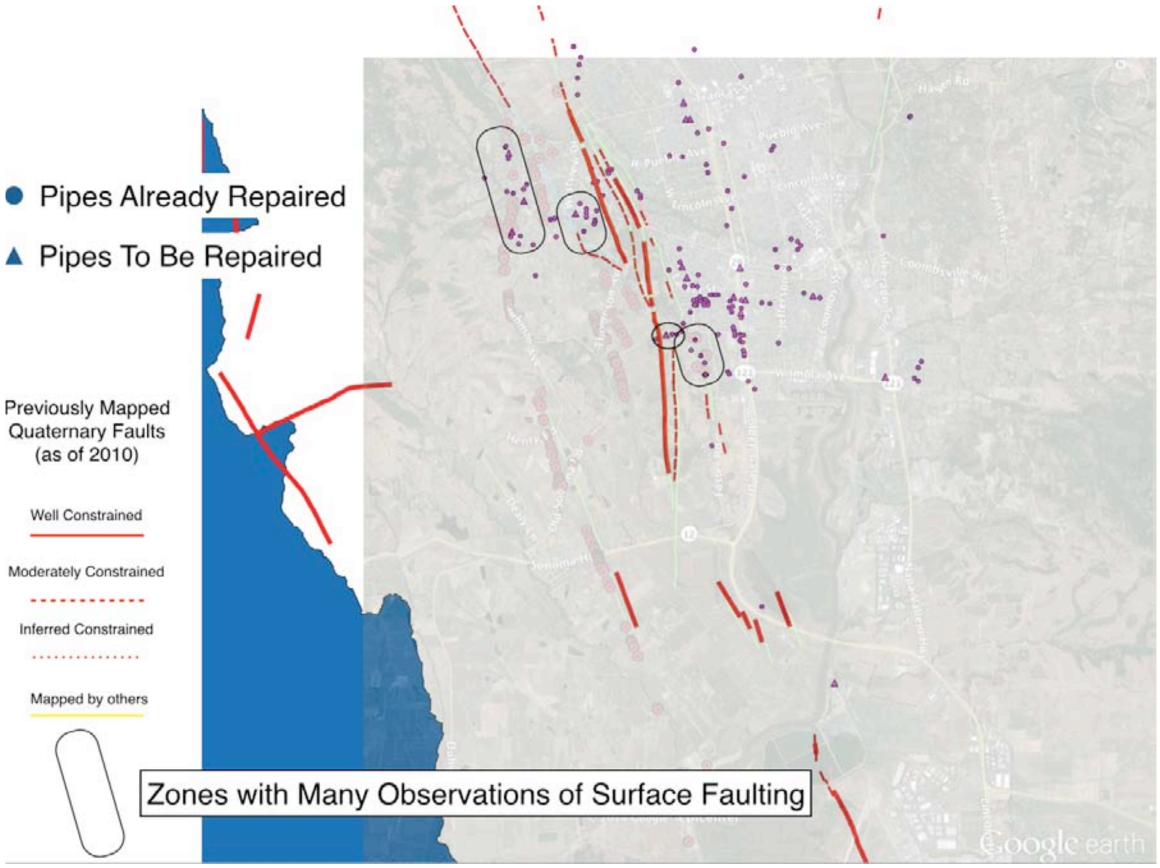


Figure 4-5. Overlay of Water Pipe Repairs and Zones with Surface Faulting

If one assumes that the pipes outside the surface faulting zones were only subjected to ground shaking effects, and uses ALA (2001) pipe fragility models, and assumes that the average PGVs were: 30 inches per second (for cast iron pipe, a lot of which was located near the fault and areas thought to potentially have higher PGVs) and 20 inches per second (all other pipes), then Table 4-3 shows the projected number of pipe repairs versus actual.

Pipe Type	Projected ALA (2001)	Napa Actual	Comment
CI	61.9	93	Very low R; very old; pulse; basin effects; shrink swell soils; low wave propagation c; high historical non-earthquake repair rates
PVC	0.6	1	
AC	3.4	5	AC 36" transmission pipe did not leak in the week after the earthquake, but did have 3 repairs in the following months. The long term repair rate on this pipe was 2 leaks per 5 years.
DI	11.4	13	
RCCP	0.3	0	
Steel	4.2	2	
Total	81.8	114	

Table 4-3. Pipe Repairs due to Shaking – Projected and Actual

In Table 4-3, there are a number of reasons for the relatively high rate of damage to Cast Iron pipe. One more reason is as follows:

- In the ALA model, the empirical observations for damage to cast iron pipe is based on the reported number of pipe repairs made after the earthquake. This number generally excludes damage that is repaired once the entire system is "put back in service".

- Therefore, the ALA value (about 82 repairs) might be a reasonable predictor of the number of pipes that are needed to be initially repaired, with a provision that perhaps 50% to 100% more repairs might occur in the ensuing several months.

In the Browns Valley area (an area with fault offsets), in the first week after the earthquake, there were 51 repairs; and between August 31 2014 and late January 2015, there were an additional 51 repairs. In this same area in the years 2009, 2010, 2011, 2012, 2013 and up to August 23 2014, prior to the earthquake, there had been 16, 17, 13, 10, 8 and 10 repairs, respectively.

In the Westwood area (an area with high ground shaking), in the first week after the earthquake, there were 68 repairs; and between August 31 2014 and late January 2015, there were an additional 38 repairs. In this same area in the years 2009, 2010, 2011, 2012, 2013 and up to August 23 2014, prior to the earthquake, there had been 19, 20, 19, 8, 10 and 5 repairs, respectively.

Figure 4-6 shows a damaged transmission line, due to rockfall (Milliken Transmission pipeline). Discussions with the City of Napa Water Department suggested that "perhaps it leaked".

Figure 4-6. Damaged Transmission Pipe due to Rockfall

Figure 4-7 shows water from a leaking distribution pipe.

Figure 4-7. Water Leaking from a Damaged Distribution Pipe

Figures 4-8 and 4-9 show damage to a roof of a steel tank in Napa. This tank is the "B" tank. The tank was constructed in 1960, with the base of the tank at elevation 400 feet. The site was originally prepared by cut, meaning that the tank foundation is atop native materials. The tank is welded steel. The roof is flat, corrugated steel, supported on 9 columns. The drain pipe, overflow pipe and inlet-outlet pipe are all located in the northeast quadrant of the tank.

- The tank shell rests in a reinforced concrete ring girder, 18-inches wide by 12-inches high. The steel shell is not anchored to the concrete foundation.

- Inside the concrete ring girder, the tank rests on about 1 inch of loose sand, underlain by a compacted, oiled sand, about 4 to 6 inches thick.

- Inlet outlet pipe. This pipe is side entry, 16 inches diameter through the tank shell reduced to 12-inch diameter at a flange. Since original construction in 1960, a ball-and-slip joint assembly was added to the outside to accommodate relative movements between the tank and the ground.

- Overflow pipe. This 8 inch diameter steel pipe has overflow elevation of 437 feet. The original 1960-vintage pipe exits the tank through the bottom plate, with center line 18 inches from the shell wall. At some time after initial construction, the overflow pipe was relocated to exit the tank mid-height.

- Drain pipe. This 8 inch diameter steel pipe exits the tank through a sump in the bottom plate, with center line 15 inches from the shell wall. Just outside the tank, the buried drain pipe has a 8-inch gate valve.

- Ventilation. At the top of the steel shell and below the roof, are a series of wire mesh ventilation screens.

The roof framing system is composed of nine 8-inch diameter steel tube columns that support three rows of 6x14 wood beams in the north-south direction. The columns rest on concrete footings, 3.5 feet square, that are placed beneath the steel plate. The 6x14 beams support 3x12 wood purlins in the east-west direction. The wood species is believed to be redwood. With water at the overflow level, there is about 0.6 feet of clear space between the water and the beams; about 1.8 feet between the water and the bottom of the purlins, and about 2.8 feet from the water to the bottom of the roof.

The initial review suggests the roof damage was due to water sloshing. This tank is 67 feet in diameter, 37 feet high (to the overflow level), with capacity of about 1,000,000 gallons. There was observed motion at the outlet pipe, suggesting that there was some wall uplift. Assuming the ground motions at this tank site were about PGA = 0.5g, and the site being rock (or very stiff soils), the ground motions at the sloshing mode might have been on the order of 0.05g or so, leading to an estimated slosh height of about (0.42 * D * SA) = 1.4 feet or so. There are no recordings at the site to determine the site-specific spectra, so the 0.05g estimate of ground motion is uncertain. In any case, with water waves of about 1.4 feet (if unobstructed), the sloshing water would have impacted the beams, and very likely the purlins. The style of initial construction might have only been so support light dead weight and live loads (total about 30 pounds per square foot), with no lateral bracing of the wood members. Thus, the water waves, travelling at several feet per second, would have produce unanticipated lateral loads on the wood beam members, easily toppling them over sideways. Once the 14-inch deep beams fall over sideways, they drag the purlins and the corrugated roof, resulting in the observed damage pattern. The City of Napa reported that some of the wood beams were found at the bottom of the tank, partially clogging the outlet pipe.

The tank did not lose its pressure boundary (likely some water was lost through the damaged roof / ventilation screens), but the tank drained rapidly all the same, owing to the damage to nearby broken pipes.

Figure 4-8. Damaged Roof of Steel Tank "B"

Figure 4-9. Damaged Roof of Steel Tank "B"

The outlet side-entry pipes used ball joint and slip joint hardware, capable of accommodating several inches of movement of the tank walls, Figure 4-10. The ball joints show evidence of rotation.

Figure 4-10. Movement of Attached Pipes

Within a month after the earthquake, the wood roof system for Tank "B" was removed, and replaced with a aluminum "dome" type roof. Figure 4-11 shows the tank on October 10, 2014. The City is considering further tank modifications, including raising the steel shell by several feet to provide more clear space for water sloshing in future earthquakes, as might be suggested by the current AWWA D100 code (2013 version). The cost effectiveness of this type of modification, as well as the AWWA code provision for providing several feet of clear space for sloshing, is uncertain, as the tank still performed (held water) in the earthquake.

Figure 4-11. Tank B, with New Aluminum Dome Roof

Figure 4-12 shows two other steel tanks in the Napa water system, photo image dated August 23, 2014 (one day before the earthquake). These tanks are in the northwest part of the city, PGA ~0.3g to 0.4g. The tank in the lower left has a corrugated steel roof, but had been taken out of service some time before the earthquake, and thus had no water in it. The tank on the right was in service at the time of the earthquake, and initial exterior inspection suggests no damage.

Figure 4-12. Two Tanks (38.2341, -122.3432)

Figure 4-13 shows a steel tank in the southwest part of Napa, built pre-1993. PGA at this location was likely around 0.4g. In mid-September 2014, it was reported that there was water observed near this tank, coming out of the ground; whether this water was from a leaking pipe, the tank, or some other source, remains unknown as of the time of writing this report.

Figure 4-13. West Side Tank (38.2631, -122.3039)

A buried concrete tank in the northeast part of Napa appears to have suffered no damage; but drained rapidly in the minutes immediately after the earthquake.

Figure 4-14 shows the restoration of water service after the earthquake.

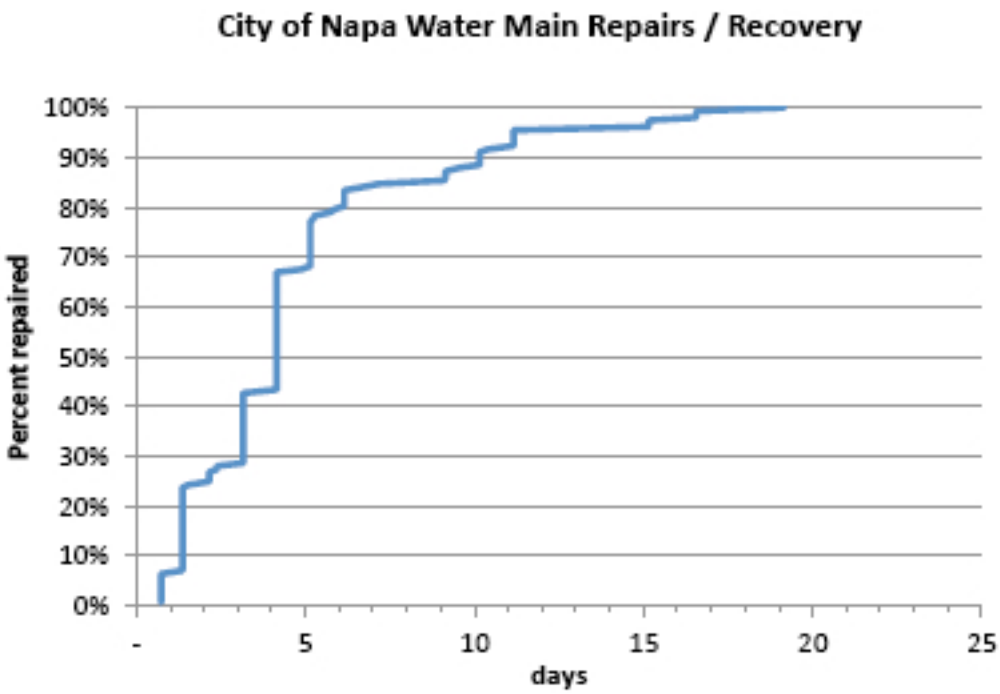


Figure 4-14. Napa Water Recovery

In making repairs, one of the required steps prior to digging up the area around the leaking pipe, is to perform "USA" markings (Underground Service Alert). This entails having each utility with underground facilities (gas, water, sewer, communications, etc.) to pre-mark the location of their pipes / conduits, prior to the commencement of digging to get to the leaking pipe. In the post-earthquake environment, when all utilities are also busy, this effort can slow down the entire restoration process. Following this process possibly slowed down the restoration effort for the water pipes. Still, the potential of accidently damaging a gas pipe, or otherwise damaging third party utilities, cannot be discounted, so this effort should be accounted for in emergency restoration plans.

Water demand increased by 200% or more immediately following the earthquake. This reflected normal overnight water demands, as well as water lost through leaking pipes, and some water being used for fire flows. As measured at the water treatment plants, the following water rates were recorded:

Time	Water Flows from WTPs	Then Known Water Leaks
Day 1. Sunday Aug 24	32 MGD	60 leaks
Day 2. Monday	28 MGD	90 leaks
Day 3. Tuesday	24 MGD	100 leaks
Day 4. Wednesday	22 MGD	105 leaks
Day 5. Thursday	20 MGD	110 leaks
Day 6. Friday	19 MGD	120 leaks
Day 20. Sept 12		167 leaks
Day 37. Oct 1		179 leaks
Day 68. Nov 1		193 leaks
Day 99. Dec 2		220 leaks
Day 153. Jan 26 2015		241 leaks

Table 4-4. Water Flows, Million Gallons per Day, Number of Repaired Leaks

The average water demand for late August, without earthquakes is about 18 MGD. The actual water flows in the entire distribution system is uncertain, but in the first day would be much higher than the 32 MGD listed in Table 4-4, in that much of the water in the 12 storage tanks (with 30 MG capacity, mostly full at the time of the earthquake) also drained in the first few hours.

Napa Water Department was aided by several regional utilities in making pipe repairs. Mutual aid (via CalWarn) pipe crews were provided by:

- EBMUD: 5 crews. Three crews were initially dispatched within 24 hours of the earthquake, and two days later, two additional crews. EBMUD reports that the EBMUD crews helped make repairs for 56 pipe leaks.
- Contra Costa Water district: 1 crew
- City of Fairfield: 2 crews
- Alameda County Water District: 1 crew

All crews arrived with spare parts, trucks and equipment, typically 5 people per crew. All mutual aid crews were released by August 29 2014 (note the slow down in the rate of pipe repairs after Day 5). It was initially thought that the mutual aid crews were sufficient to effect nearly all the pipe repairs by August 29; however, over time, as the last pipe repairs were made, additional pipe leaks were identified as repaired pipes were re-pressurized.

The Napa Water Department estimated they spent about $200,000 on spare parts.

There were no regional-wide boil water alerts issued during or after the earthquake. Water quality at the water treatment plants was reported to be acceptable. The general population was encouraged to use bottled water (many did). There were boil water alerts to all customers who lost water supply, owing the concern of possible cross contamination from nearby potentially damaged sewer lines (no evidence that this occurred); or bacterial growth in empty water pipes.

The lack of a regional boil water alert was in part due to the negotiations between the Napa Water Department and other California state-wide agencies. The state-wide agencies wanted a large scale boil water alert, being concerned that damaged sewer pipes might be leaking sewage into damaged water pipes. However, the City of Napa noted that they had no damage in the transmission pipes, and the water treatment plants were able to keep up with the increased water demand (for normal use lost water due to leaks, and fire fighting purposes), and positive pressure was maintained in the majority of the water system, so there was no need for such a regional boil water alert. Had the water transmission pipes been damaged, or the water treatment plants been unable to keep up with post-earthquake water demands, large portions of the water system would have become de-pressurized, and this would have had much more impacts on customers (more outages, boil water alerts, longer restoration times, etc.).

At some locations, the City of Napa installed hose bibs, Figure 4-15, at working fire hydrants with potable water, and alerted residents where they could go get potable water. These were located close to locations where there were water pipe breaks and with residents without piped potable water.

Figure 4-15. Hose Bib Used During Recovery

By August 28, there were about 500 Napa customers without water. By August 29, this was reduced to about 400 customers, with the intent to have all customers back in service by August 30.

4.2 City of Vallejo System

In Vallejo, early reports showed 16 water pipe repairs; final data is not yet available, but latest information (as of late September 2014) suggest about 80 repairs. The bulk of these repairs are reportedly in areas of Vallejo sometimes described as "marshes".

4.3 DWR - NBA

The North Bay Aqueduct (NBA) delivers raw water to the Jameson Canyon Water treatment plant. The NBA was constructed in two phases. Phase I was built in 1967-68 to serve Napa County, and Phase II extended the aqueduct from Cordelia to its permanent water source at Barker Slough, in the North Sacramento – San Joaquin Delta.

The diameter of the buried pipeline varies between 3 to 6 feet, and capacity steps down from 175 to 39 cubic feet per second The pipeline is composed primarily of precast, pretensioned concrete cylinder pipe. This pipe would have been exposed to PGA from 0.02g to 0.15g (or so) along its alignment.

DWR inspected the facility after the earthquake, and found no damage.

4.4 St. Helena

The following incident occurred to the water system at the St. Helena Hospital, which has its own system separate from the City of St. Helena: tank with sedimentation issues led to water quality issues in the distribution system.

Something similar is reported to have occurred within the City of Calistoga water system.

4.5 Water System Near Epicenter

West of the City of Napa, water is supplied to rural areas by local wells. This area is not connected to the City of Napa water system.

The Meyers Water Company has one well, located about 1,000 feet from the epicenter. At this location, its 4,000 gallon pressure tank slid, moving about 5 to 10 feet off its concrete foundation.

4.6 Napa Sanitation District

Wastewater from the City of Napa and surrounding unincorporated areas is treated by the Napa Sanitation District (NSD). The NSD also produces recycled water at the Suscol Water Recycling Facility (SWRF).

NSD provides sanitation sewer service to about 75,000 people over 23 square miles. There are 36,000 residential and business connections.

There are 270 miles of collection lines and mains, ranging from 4-inch to 66-inch diameter. There are 3 lift stations (Stonecrest, Riverpark and West Napa, largest is 3 MGD at the Napa River crossing), and 5,651 manholes.

The Suscol Water Recycling Facility (Figure 4-16) has tertiary treatment, with average day flows of 7 MGD (dry weather conditions). The plant includes the following facilities: flocculating clarifiers; secondary effluent pump station; backwash filters; disinfectant rapid mixing; chlorine contact basins; recycled water storage reservoirs; recycled water pump station.

Figure 4-16. Suscol Wastewater Treatment Plant

Figure 4-17 shows the location of the SWRF, as well as the recycled water pipes.

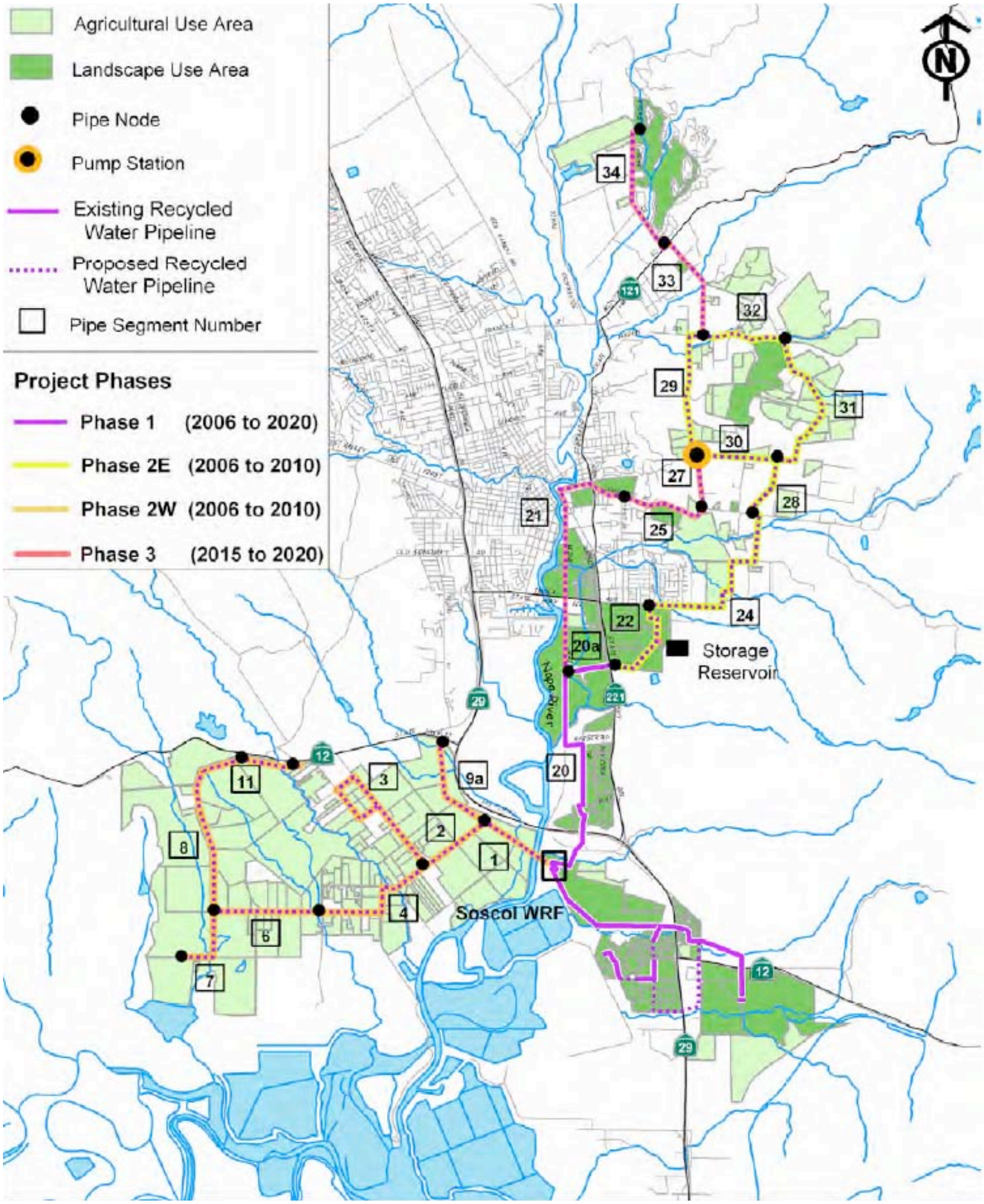


Figure 4-17. Napa Recycled Water System

Figure 4-18 shows the recycled water storage reservoir (PGA ~0.15g).

Figure 4-18. Recycled Storage Reservoir

Figure 4-19 shows the locations of the sewer line breaks where repairs were made shortly after the earthquake (red dots). The red dots near Meadowbrook are all nearly coincident (within about 100 feet or so) with observed surface faulting.

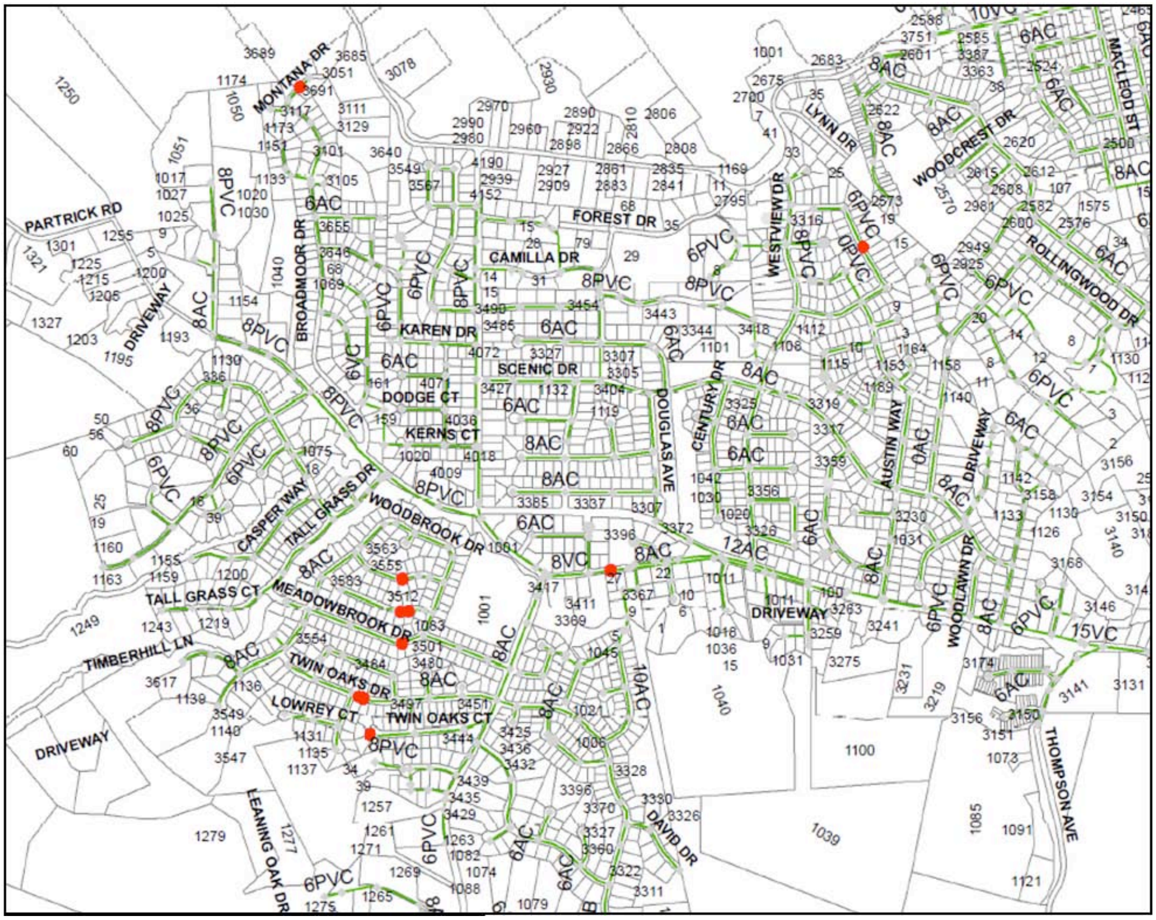


Figure 4-19. Location of Sewer Breaks

Through September 15, 2015, NSD reported 11 breaks (possibly 13?) in sewer mains (all AC). Of these breaks, 9 were along the fault trace, and 2 were due to washouts from nearby water main breaks.

The Central Contra Costa Sanitary District sent a TV truck to assist NSD. NSD inspected only its large trunk lines and those that crossed the fault.

The typical repair strategy across the fault was to insert a PVC-type bladder within the broken pipe, then inflate and set the bladder. NSD reports that this effort was successful.

In discussions with NSD, it was mentioned that in fact NSD's much lower "repair rate" (11 breaks) compared to NWD's repairs (over 170 repairs), might not necessarily mean that NWD's pipes are "much better". Instead, it might well be that many of NWD's are leaking, but as sewer pipes are not pressure pipes, the leaks go into the ground and are not apparent at the surface. NSD reports that only its largest pipes had been videoed after the earthquake (only a few percent), so, by mid-September 2014, there was no direct observations of the condition of the vast majority of the sewer pipes. Also, as noted in Table 4-5, the vast majority of NWD's pipes are non-metallic, meaning the effects of external corrosion due to hot soils / high ground water table are negligible.

Type	Miles	Pct of Total
ABS Plastic	2	0.7%
AC	124	45.9
CI	1	0.4
Concrete	3	1.1
PVC	61	22.6
RCP	7	2.6
VCP	70	25.9
Other	2	0.7
Total	270	100%

Table 4-5. Length of Sewer Pipes – Napa (Miles)

There was minor cracking of reinforced concrete at the SWRF. There was sloshing and spillage at sand filters.

A brief inspection of the sewer plant identified the following:

- All facilities at the plant are modern, and all presumed to have been designed for seismic "Zone 4" motions. With various vintages of codes, the design procedures have varied over time. Generally, the minimum earthquake forces would have been about PGA = 0.4g, and most (or all) of the facilities would have been designed with an essential facility in mind, meaning at least a 25% increase in forces used for design.

- The office buildings are low rise structures. There was little damage to the structures; all were operable.

- There are a variety of reinforced concrete tanks and basins at the site. It is thought that all of these are founded on reinforced concrete mat foundations; piles were not used.

- We observed little evidence of liquefaction at the main site. There were no differential settlements between pipes coming out of the sides of tanks and the adjacent ground.

- At one location, a large pipe that enters a tank had a distressed Dresser-type coupler (slip joint). Figure 4-20 shows one of the two such pipes (the other pipe leaked); both have essentially the same details. This leak was attributed to high inertial ground shaking, rather than differential settlements. The shaking caused some movement at the slip joint. The leak was solved by re-tightening the bolts that make the connection (top right part in Figure 4-20).

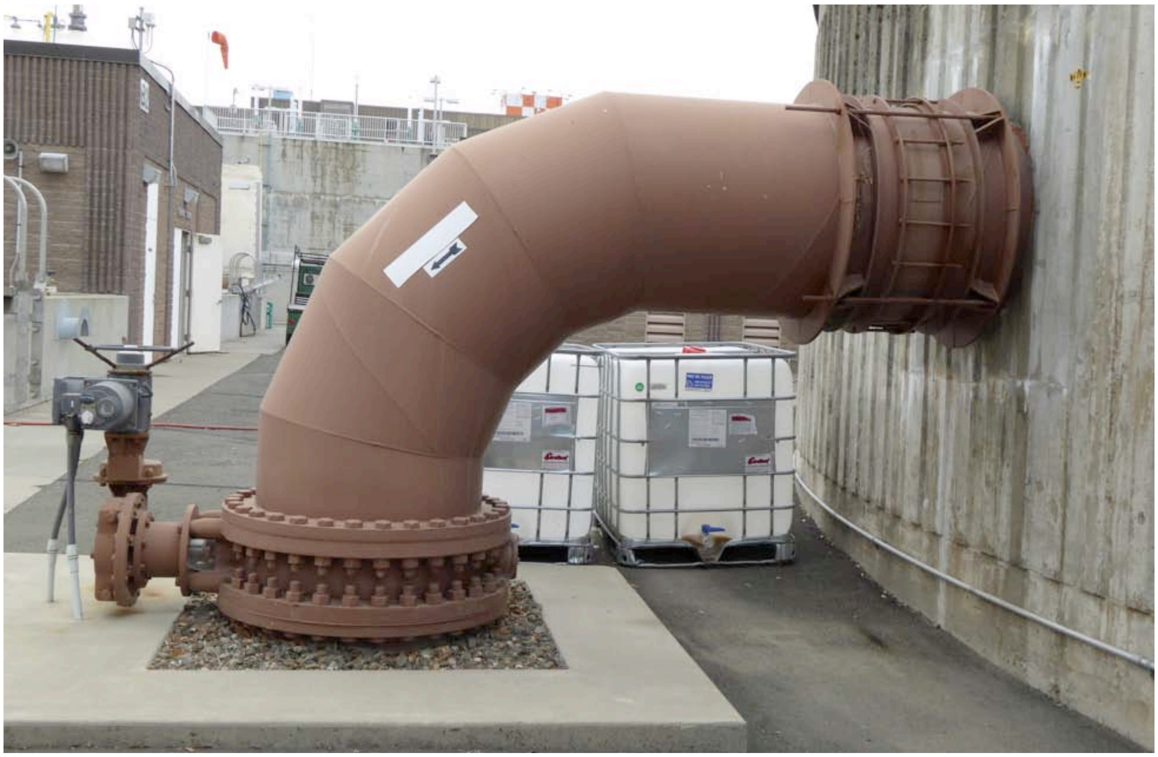


Figure 4-20. Steel Pipe with Dresser-Type Coupling

A spring-mounted motor system suffered some damage, Figure 4-21. This assembly is attached to an adjacent large diameter steel pipe. During normal operation, the spring mounts allow minor movements (commonly under 1/16th inch) of the motor assembly. To accommodate these movements, the attached pipe is supported on a concrete pedestal, and a rubber-type connector is used between the pipe and motor assembly. The earthquake broke the first pipe support. This pipe support had already sustained considerable damage due to corrosion, prior to the earthquake, and the incremental forces applied during the earthquake failed the support.

Figure 4-21. Spring-Mounted Motor Assembly

All chemical tanks at the site had been seismically braced prior to the earthquake. No damage to these tanks was observed.

There are two circular secondary clarifiers at the site. At the time of the earthquake, one was not in use (and empty) (Figure 4-22), and the other was full of water (Figure 4-23).

In Figure 4-22, the heavy steel bracing for the water trough is seen. The water level in this clarifier at the time of the earthquake corresponds to the water (with algae, etc.) seen in this photo. A complete drain of this tank had not been done within 7 weeks of the earthquake; but as the water level was very low at the time of the earthquake, it is not expected that there would have been any damage to the central tower due to unbalanced water loading due to the sloshing effects.

Discussion with plant staff indicate that there might have been some slight rocking of the central tower of the full clarifier in Figure 4-23, as the inside baffle (steel plate) seems to be slightly tilted; but as of 7 weeks post-earthquake, the clarifier had not been drained to verify the condition of the tower anchor system. While water sloshing as certain to have occurred, as the earthquake occurred during the night-time, there was no one there to observe the actual wave heights; there were no reported obvious solids on the ground adjacent to the clarifier.

Figure 4-22. Empty Clarifier

Figure 4-23. Full Clarifier

The SWRF did not lose PG&E power, and the SCADA system was not interrupted. At the plant, there were many instances of items thrown out of bookshelves, but none of the desk-top LCD-type displays (with no special seismic anchorage) toppled over. This suggests that the actual level of shaking at the plant site was on the order of PGA = 0.3g to 0.5g or so; if ground motions had been even higher (say PGA > 0.7g), one would have expected at least some of the desk-top monitor to topple.

The 3 lift stations did lose PG&E power; each had backup power.

The biggest incident was that the SWRF had a "plant upset". That is a significant amount of spilled wine entered the sewer system and the plant. BOD went from a normal of 175 mg/l to 15,600 (due to high sugars) and pH dropped to 5.5. This disrupted the anaerobic bacterial treatment (the bugs went to sleep). The remediation was to blow air into the digester for 24 hours (using normal blowers), and the process was recovered. The total amount of wine spillage has been estimated (upper bound) at 334,000 gallons (equivalent to about 6,800 barrels). There was no release of untreated water or solids.

4.7 Sonoma Valley Community Sanitation District

The Sonoma County Water Agency operates water and wastewater system throughout Sonoma County. In the city of Sonoma, where ground motions were between PGA = 0.07g and 0.17g, there were no reported pipe breaks. At the wastewater treatment plant located south of the city of Sonoma, there was no reported damage, and water did not slosh over the walls of the clarifiers.

5.0 Performance of Highway Bridges

On Sunday, August 24, 2014 at 3:20 AM PDT, a M6.0 earthquake struck south of the city of Napa (38.22° N, 122.31° W), in Napa County, at a depth (hypocenter) of 11 km. This is the third significant earthquake to impact the area over the last 25 years. On October 17, 1989 the M 6.9 Loma Prieta earthquake occurred 100 km to the southwest, and damaged several bridges in the region due to amplification of long period motions in the unconsolidated soft sediments. The September 3, 2000 M 5.2 Napa Earthquake caused a great deal of damage to waterlines, power lines, and houses, but little significant damage to bridges (Eidinger and Yashinsky, 2000). Experience with previous seismic events has shown bridge damage seldom occurs for earthquakes with magnitudes less than 6.0. However, it was unexpected to see such large recorded ground motion during this earthquake, especially by the Carquinez Bridge, 15 miles from the fault rupture (but see Section 2, showing that the instrumented high motions in the high frequency range were most likely caused by moti0ns of the bridge, and not a true representation of the free field ground motions).

This report examines the performance of three bridges in the area, and Highway 37. Caltrans has developed a comprehensive report covering some 412 bridges in the area, most of which had no damage (Yashinsky et al, 2014).

The South Napa earthquake occurred in a seismically active region within the San Andreas fault system. The San Andreas system contains many right-lateral strike-slip faults that form the boundary between the Pacific plate and North American plates. In Figure 5-1, the location and extent of the observed fault rupture is shown in red, and the prior mapped locations of faults shown in orange. The insert shows the location of the epicenter in relation to the San Andreas fault system.

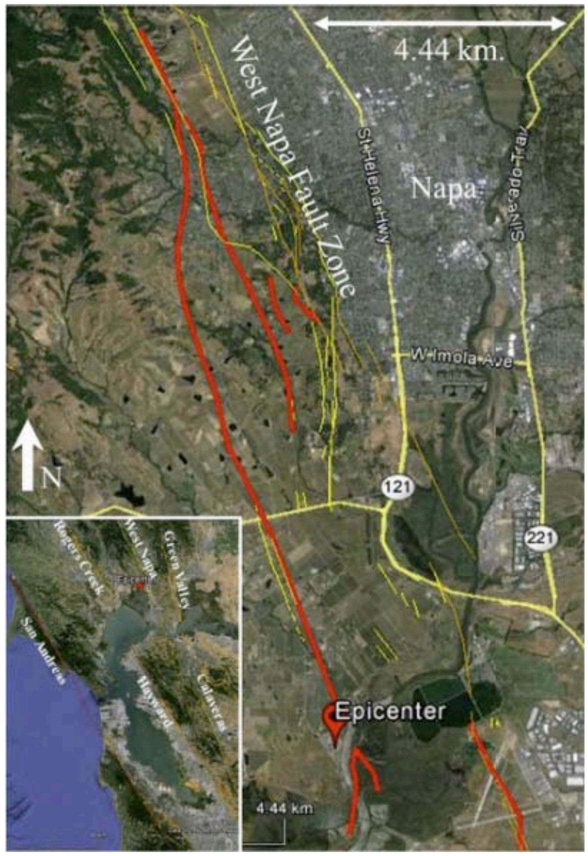


Figure 5-1. Aerial view showing epicenter of the South Napa earthquake and location of nearby faults

The northern end of San Pablo Bay is tectonically constrained on the west by the (orange) Hayward-Rogers Creek Fault System and on the east by the (orange) Concord-Green Valley Fault System. The fault with the most recent movement close to the earthquake epicenter is the West Napa Fault. The 2000 M 5.2 Napa earthquake was also thought to have been caused by the West Napa Fault but is now thought to have been located three miles to the west of the northern extent of the West Napa fault[2].

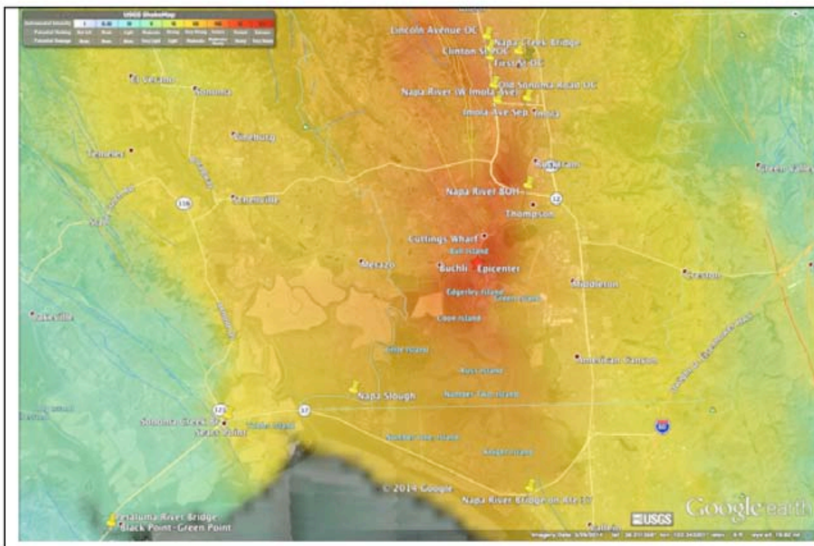
The August 2014 earthquake ruptured 11 km below the ground and caused a surface rupture from the epicenter to the northwest for about six miles along a previously mapped strand of the West Napa Fault: the Browns Valley section. At this point the surface rupture jumped ½ mile to the east and continued on an unmapped strand of the West Napa Fault for several more miles. Ground motion recordings indicate that the fault rupture, propagating to the northwest, released a strong pulse towards the City of Napa.

Performance of State Bridges: There are several reasons why very little bridge damage occurred during the South Napa Earthquake. A magnitude 6.0 earthquake usually doesn't

[2] USGS Earthquake Hazards Program: http://www.strongmotioncenter.org/NCESMD/data/yountville_03sep2000/eqinfo.htm

have enough energy to cause significant bridge damage. Also, the most vulnerable bridges had been retrofitted. Out of 412 bridges in Solano, Napa, and Sonoma Counties 54 bridges had been retrofitted and the others were screened in the 1990s and found not to be significantly vulnerable.

The earthquake occurred on Sunday at 3:20 AM. Caltrans Structure Construction and Structure Maintenance teams drove into the area after the earthquake and reported that there was only minor bridge damage. The next morning a bridge investigation team consisting of Mark Mahan, Don Lee, Mark Yashinsky, and Ron Bromenschenkel from Caltrans Office of Earthquake Engineering and Robert Zezoff from Caltrans Office of Structures Local Assistance drove to the area to evaluate how the bridges performed. The bridges investigated are shown in Figure 5-2; the performance of three bridges are reported herein; for the other bridges, some of which suffered relatively minor damage, and some relatively major damage, see Yashinsky et al (2014).



Napa River Br	23 0064
Napa River BOH	21 0049
Napa River (Imola)	21 0108LR
Imola Ave Sep.	21 0086L
Old Sonoma Rd OC	21 0087
First Street OC	21 0088
Lincoln Ave OC	21 0089
Sonoma Creek Br	23 0063
Petaluma River Br	27 0013
Napa Slough Br	21C0117
Greenwood Ave Br	21C0042
Clinton St POC	21C0094
Third St (Napa R) Br	21C0012

Figure 5-2. Bridges investigated after the August 24 2014 earthquake

5.1 Napa River Bridge on Route 37, 23-0064.

*Figure 5-3. Napa River Bridge on Route 37 Br. #23 0064 (**38.1203°, -122.2800°**)*

Bridge 23-0064 is a 33 span precast girder bridge on flexible two column piers and stiff four column piers that was built in 1963. Like many river crossings it starts at ground level and then quickly rises to provide clearance over the river. A problem with many precast girder bridges is that they are not well designed for earthquakes. The girders need to be continuous to protect the superstructure and force plastic hinging into ductile columns. The girders on the Napa River Bridge were inadequately developed and they pulled out of the end diaphragms during the 1989 Loma Prieta earthquake. The bridge was repaired after the earthquake and got a very thorough seismic retrofit in 1996. The retrofit included bolsters around the end diaphragms to make the girders more continuous, also transverse prestressing, with additional seat width, and pipe seat restrainers at the hinges. The foundations were retrofit with additional piles and a bigger pile cap. All of the columns were encased in steel jackets. A downhole array[3] was installed at the bridge, which recorded 0.2g acceleration, 19 cm/s velocity, and 2 cm displacement at the ground surface during the South Napa Earthquake. The bridge was also instrumented with Channels 1, 2, and 3 between piers 13 and 14 at the top of the bridge, which recorded 0.53g acceleration and 14.7 cm (about 6 inches transverse) of displacement. The ground motion and structural excitation were not high enough to cause serious damage to a well-designed or to a seismically retrofitted bridge. The only damage to the Napa River Bridge was that the expansion joints opened and closed enough to damage a few of the type B joint seals which had to be replaced. The hand railing at the

[3] http://www.strongmotioncenter.org/cgi-bin/CESMD/iqrStationMap.pl?ID=AmericanCanyon_24Aug2014_72282711

expansion joints opened up enough to cause the bridge crews who first inspected the bridge to close it as a precautionary measure.

Figure 5-4. Napa River Bridge on Route 37 Br. #23 0064

Figure 5-5. Damage to Napa River Bridge during the Loma Prieta 1989 Earthquake

Figure 5-6. Retrofitted Napa River Bridge with Steel Column Casings and Enlarged Footings

A strong motion instrument downhole array[4] was installed at the bridge, which recorded 0.2g acceleration, 19 cm/s velocity, and 2 cm displacement at the ground surface. The bridge was also instrumented (see Figure 5-7) with accelerometers between piers 13 and 14 at the crest of the bridge, which recorded 0.53g acceleration and 14.7 cm (about 6 in transverse) of displacement (Figures 5-8 and 5-9).

[4] http://www.strongmotioncenter.org/cgi-bin/CESMD/iqrStationMap.pl?ID=AmericanCanyon_24Aug2014_72282711

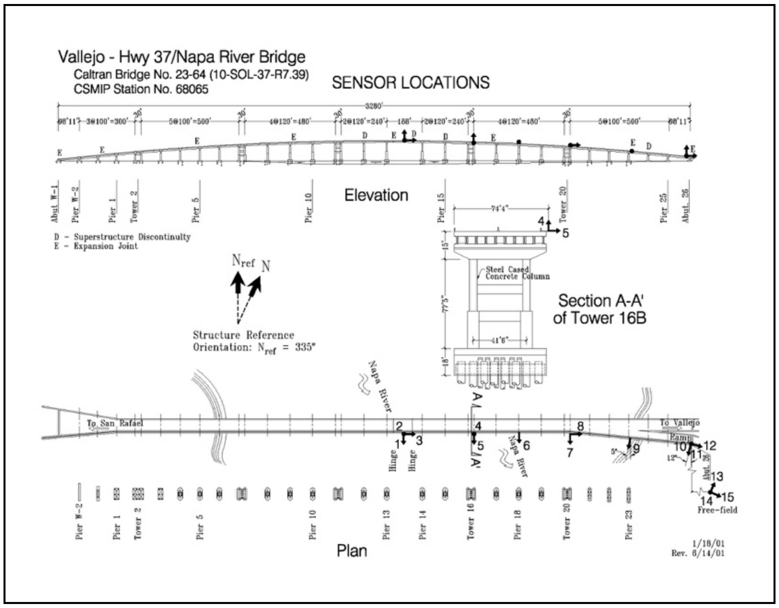


Figure 5-7. Location of Instruments on Napa River Bridge on Route 37

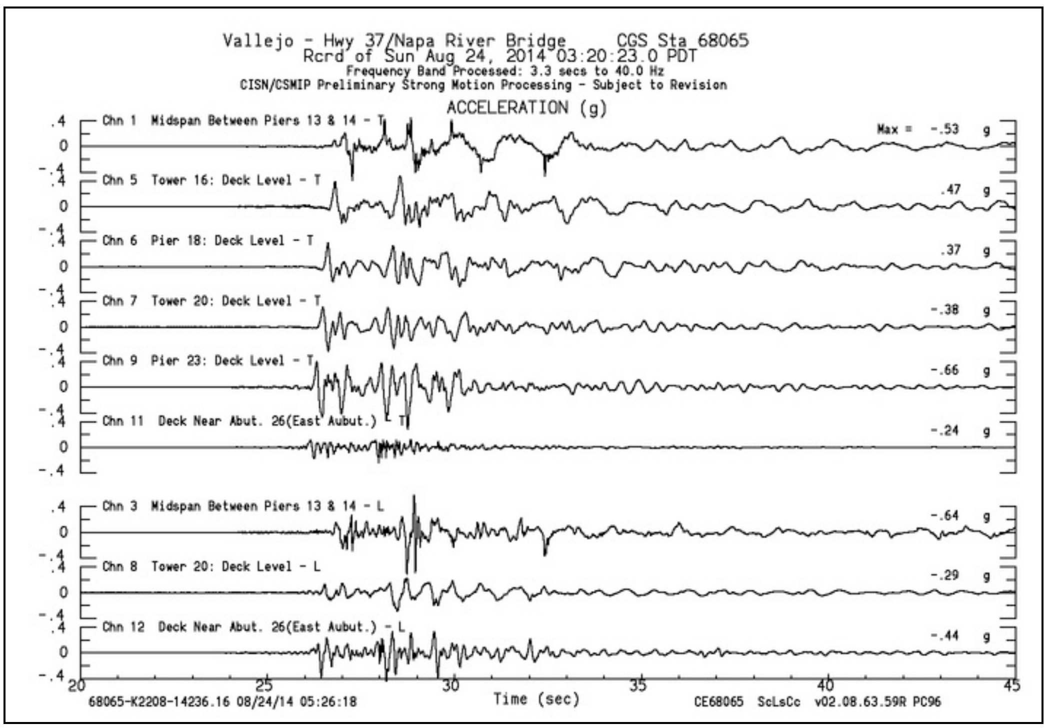


Figure 5-8. Acceleration Records on Napa River Bridge on Route 37

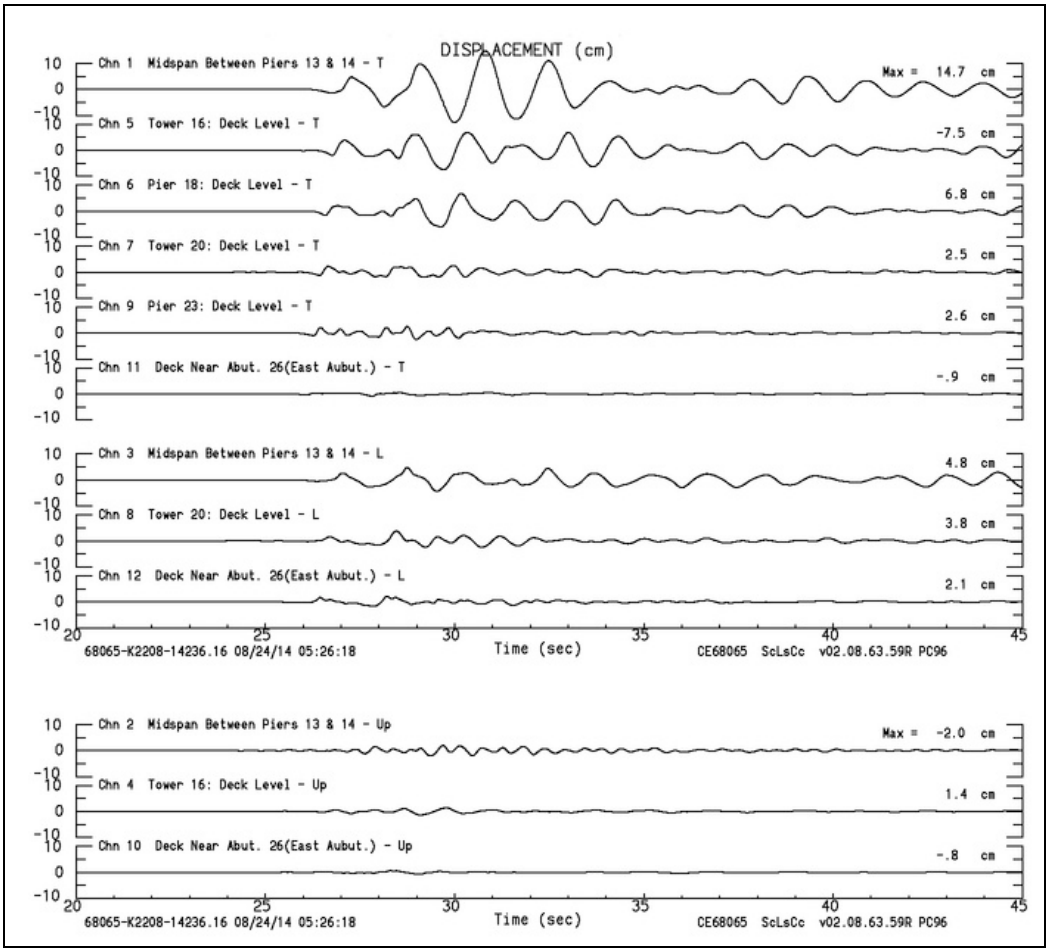


Figure 5-9. Displacement Records on Napa River Bridge on Route 37

The only damage to the Napa River Bridge was that the expansion joints opened and closed enough to damage a few of the type B joint seals which are to be replaced. The hand railing at the expansion joints opened up enough (Figure 5-10) to cause the first responders to close the bridge as a precautionary measure. When Caltrans bridge engineers arrived at the bridge, a quick inspection showed them that there was no serious damage and they re-opened it to traffic.

Figure 5-10. Damage to the Napa River Bridge was Permanent Longitudinal Displacement at the Expansion Joints

5.2 Bridge 21-0049

Bridge 21-0049 is a 13 span prestressed concrete continuous box girder bridge on single column bents that was built in 1977, Figure 5-11. The bridge is 2,230 ft long with a 250 ft long span over the Napa River. This bridge was built after the 1971 San Fernando Earthquake and consequently it was designed for earthquakes. The columns had good confinement and the in-span hinges were well designed. Apparently, the foundations were felt to be under-designed because they were retrofitted with additional piles in 1994.

*Figure 5-11. Napa River Bridge on Route 29 Br. #21 0049 (**38.1245°, -122.285°**)*

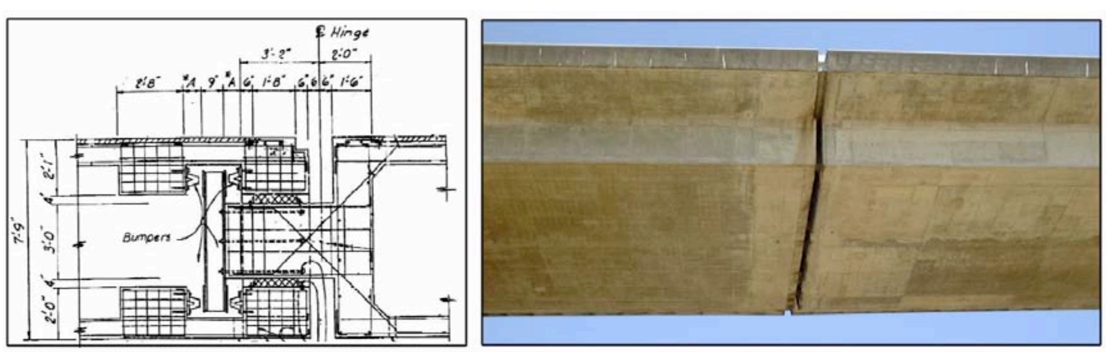


Figure 5-12. Unusual in-span hinges on the Napa River BOH

This was the closest bridge to the earthquake epicenter (about 2 miles). Although the bridge wasn't instrumented there was a station nearby at Napa College (red dot) that recorded peak ground motion of 0.375g (Figure 5-13).

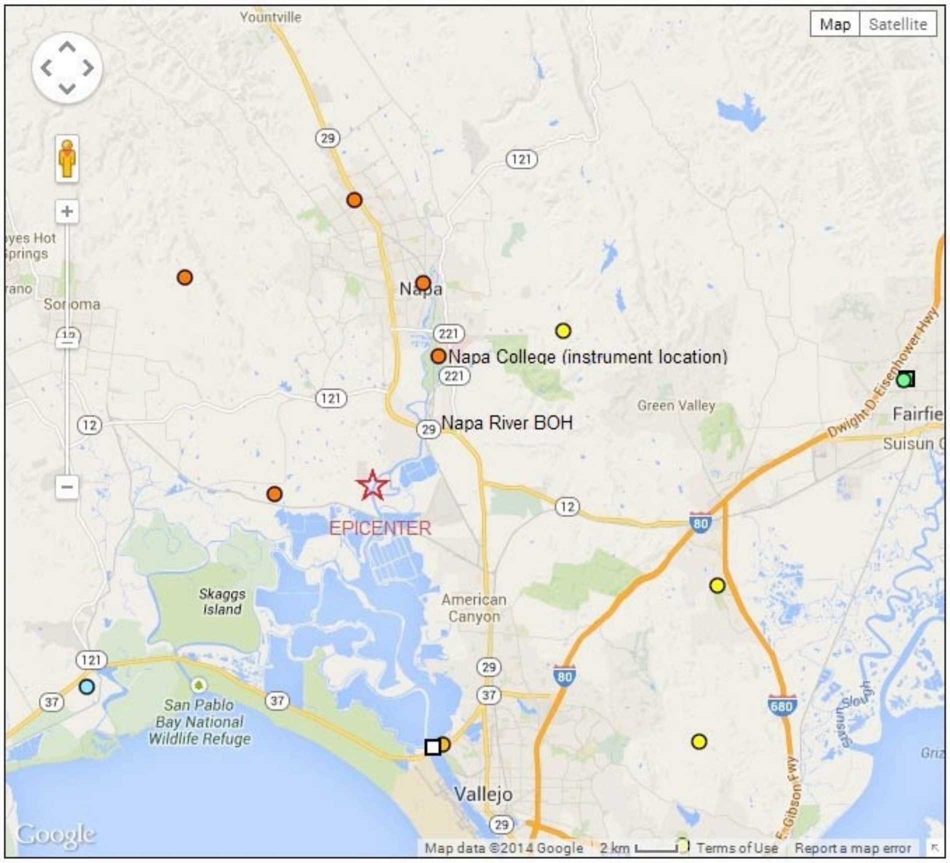


Figure 5-13. Map showing epicenter, bridge, and instrument locations

The only damage during the earthquake was at Abutment 14 on the west side of the river, The wingwall on the left side of the abutment settled one inch and rotated outward two inches. Where the abutment was in contact with the wingwall it has a concrete spall of six inches by six feet with exposed reinforcement (see Figure 5-14).

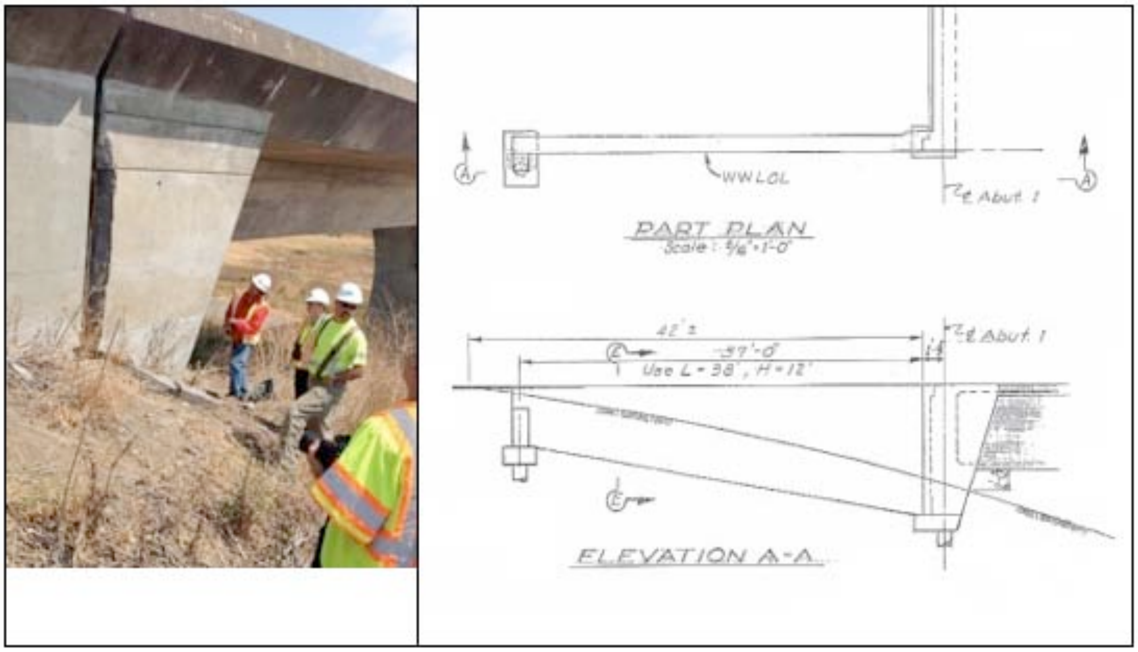


Figure 5-14. Abutment 14 concrete spall on the Napa River Bridge and Overhead

5.3 Bridge 21-0108 L/R

Bridge 21-0108 L/R is a pair of bridges that were built in 2007, Figure 5-15. They are 13 span (2143 ft long) prestressed concrete continuous box girder bridges on single column bents. These nearly new bridges have not been retrofitted.

*Figure 5-15. Napa River (West Imola Avenue) Bridge Br. #21 0108L/R (**38.2814°, -122.2842°**)*

When the investigation team first saw the abutments on the West Imola Avenue Bridges, it was assumed there was soil behind them that was held in place with mechanically stabilized earth (MSE) retaining walls. However, when they looked behind the abutment, it was seen that the approaches were actually slab bridges on pile extensions. What had been thought to be MSE Walls turned out to be curtain walls. Caltrans prefers to have soil behind the abutment to provide stiffness and damping during the earthquake. However, on such a long bridge a stiff abutment plays a much smaller role.

This bridge is also very close to the Napa College station that recorded peak acceleration of 0.375g during the earthquake. The damage that occurred during the earthquake, cracks and spalls of the curtain walls at all the abutments, was the result of the ends of the superstructure banging against the slender curtain walls (Figures 5-16 and 5-17). More substantial abutments could have held the superstructure more securely in place. However, it is unlikely that the superstructure could unseat since the approach slab is securely attached to the end of the superstructure. Also, when Caltrans Office of Structures Maintenance and Investigations (OSMI) went inside the superstructure, they found the hinge restrainers had been poorly installed and were damaged at the swage connections or at the tension indicators (Figure 5-18). Restrainers must be carefully installed, which requires tightening them until the spiral washers close and then backing off to account for the variation in temperature. However, restrainers are a secondary system for earthquake protection and the hinges all had 36 inch seats.

Figure 5-16. Outside and Inside of an abutment on the Napa River (West Imola Avenue) Bridges

This bridge had the most expensive repair ($350,000) of all the bridges.

Figure 5-17. Close-up of damaged curtain walls on the Napa River (West Imola Ave) Bridge

Figure 5-18. Restrainer damage at Hinge 10, Bay 2 of Napa River (W. Imola Ave) Bridge

5.4 Highway 37

Highway 37 is located along the north shore of San Pablo Bay. Other than damage where the road transitions to a bridge (differential movements, described in Section 5.1 above), there was no observed damage to this road between Novato and Vallejo: no lateral spreads or material cracks in the asphalt surface. This road is mapped as being almost entirely in "high" liquefaction susceptibility zones, with PGA > 0.2g for much of the length, one would have surmised some type of liquefaction damage, but none has been observed. One suspects that the liquefaction maps of Sowers (1998) Knudson (2000) and Witter (2006) may deserve some refinement.

6.0 Communications

6.1 AT&T

The performance of AT&T's communication systems in this earthquake is generally "good", although some issues arose.

Figure 6-1. AT&T Building on Clay Street, Napa

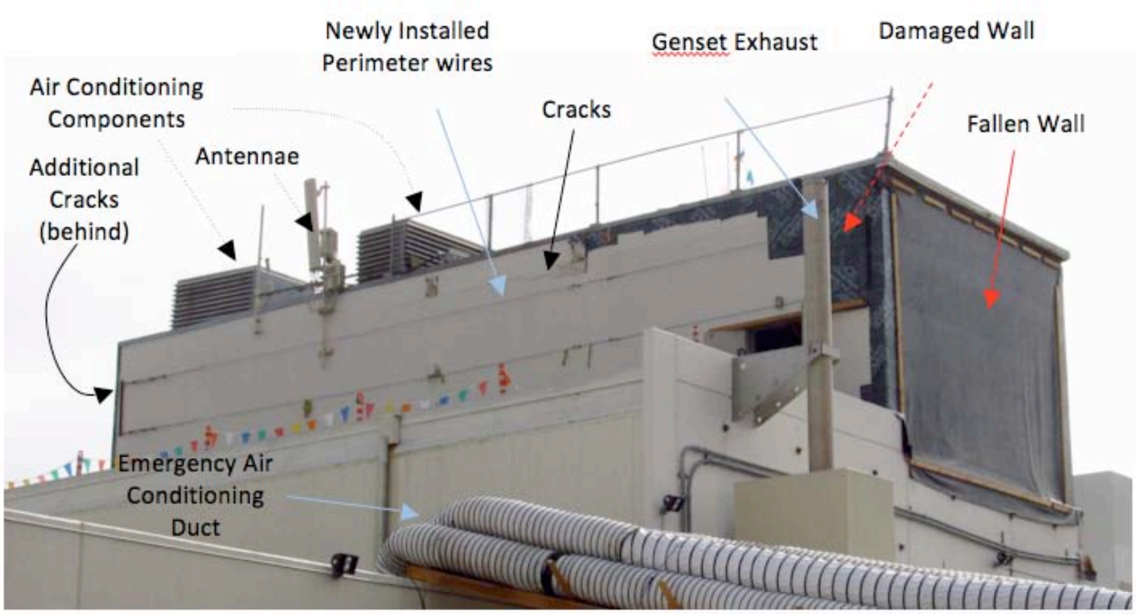


Figure 6-2. AT&T Building on Clay Street, Napa

The ATT building on Clay Street in downtown Napa was damaged, Figures 6-1, 6-2.

The concrete wall panel that has been displaced was apparently a "knock-out" type panel, to allow for future expansion of the facility. The panel was attached to the rest of the building using eight angles, bolted to the panel and to the building (Figure 6-4). Apparently, shaking of the building resulted in excessive forces on the bolts, and the connections failed, allowing the panel to fall.

Cracks along at least two other walls of this penthouse (Figure 6-3) and damage to a corner next to the fallen wall seem to indicate that additional issues may have been present in this room. The fact that a large cooling unit that had been situated on the roof of this penthouse (see Figure 6-4) was removed shortly after the earthquake may also indicate that this room experienced other structural damage in addition to the fallen wall and that there could have been concerns that the earthquake weakened this room considerably.

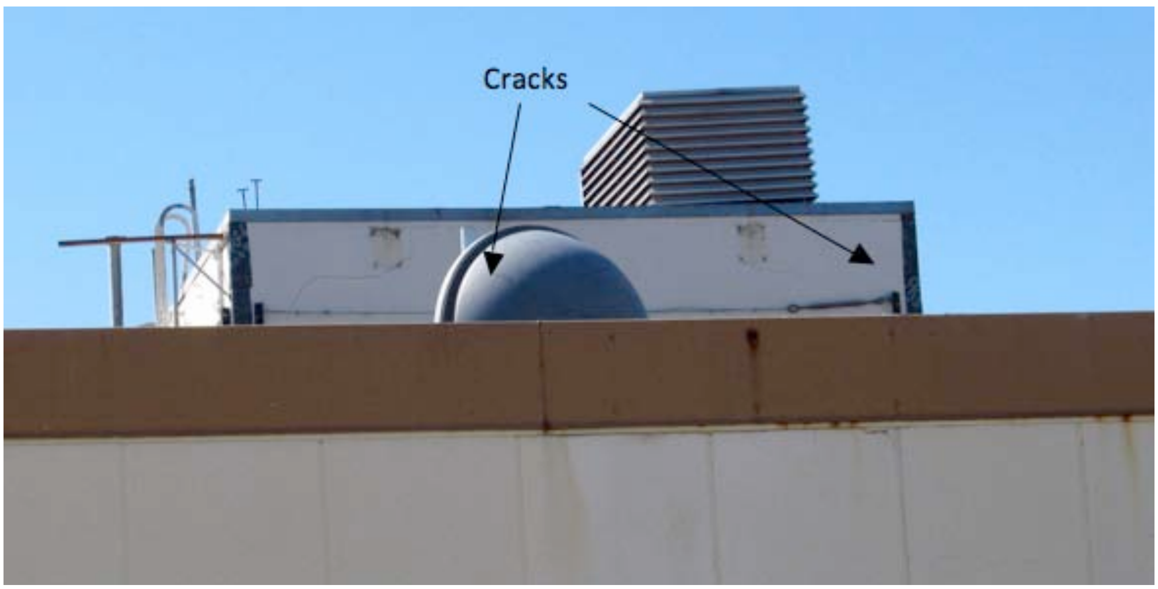


Figure 6-3. Additional cracks in the wall opposite to the one that fell

When the panel fell, it damaged a water pump that is part of the HVAC system for the site, and severed the PG&E power supply into the facility. Additionally, the wall severed a fiber optic cable to a wireless base station located in this upper room causing it to lose service due isolation from its switching center. Also, the emergency generator seem to have experienced some issue and failed to work. Battery systems did work, and the batteries sustained the communication equipment and operations. However, as air conditioners are not connected to the DC bus, they cannot be powered by the batteries. This intrinsic system vulnerability in combination with damage to a water pump and other potential damage to ducts or other components of the HVAC required the deployment of an external emergency ventilation unit, shown in Figures 6-5 and 6-6, in order to keep the heat down in the building. Both figures also show a large portable generator deployed to this site. Images on a TV report produced by Dan Noyes and aired by KGO shows an air compressor outside the central office which likely was used to keep cables pressurized after the onsite pressurization system fail when the onsite generator did not work following loss of electric supply from damage caused by the fallen wall (as also indicated in the same report).

Figure 6-4. Providing External Services to AT&T Building

Failure of air conditioning systems and/or generators or other potential service affecting issues related to power equipment due to collapsed walls is a failure mode that has been previously observed in several past earthquakes, including Haiti and Chile (both in 2010). Moreover, the same failure mode was observed during the Northridge earthquake in 1994. Furthermore, potential for service affecting issues due to wall damage was not only observed after earthquakes. Hurricane Katrina destroyed an exterior wall of the generator room at Bellsouth's (now AT&T) Gulfport central office. As a result of these observations it is recommendable to examine construction practices in central offices and to perform an inventory of current conditions in order to identify potential structural issues that could produce damage in a future events. Such inventory could be used to plan the necessary mitigation measures to prevent future damage to happen.

In addition to cell service loss of service, some unconfirmed reports (denied by AT&T) indicated some land-line service was down (not available) on Sunday morning, August 24, 2014. Reportedly, the 911 system remained on line.

According to unconfirmed sources from AT&T, there was some "iron-work" damage within the building. By this, it is usually meant cable trays that are located above equipment. We did not have direct access to inspect this damage; it is suspected that any such damage apparently did not damage the actual power and communication cables.

Figure 6-5. AT&T Building on August 25, 2014

Figure 6-6. Parking Lot, with mobile generator on left and a mobile ventilation unit of the right. Photo taken on October 10, 2014

6.2 Verizon

The performance of Verizon's communication systems in this earthquake is generally "good", although some issues arose. Verizon has reported the following.

After the earthquake, the Operations Team manger contacted employees to verify their status and determine if they needed help. Team members were asked to check on their families and property first. Employees used text messaging to update the Operations Manager on their status and availability.

In some cases, staff used Satellite phone to communicate as the Verizon network was already becoming congested with a large increase in call volume.

Immediately after the earthquake, cell site status was as follows:

- 1 cell site was off the air. This is a roof top site, located in downtown Napa. The building it was on was red-tagged with significant damage. The façade of the cell site structure around the equipment platform was damaged. The shaking of the equipment also damaged antennas and antenna feed lines. Power cabinets repairs had to be made before a portable generator could be connected, Verizon had to work with local Fire Department personnel and the building owner to gain access and clear space to park the emergency generator. The site was off the air due to the antenna system damage. Once access was arranged, repair staff were able to restore partial service by 1 pm, and full service by 7 pm, August 24.

- 12 cell sites were without PG&E power. Of these, 8 were on generator power, and 4 were on battery power. The battery power sites were in Browns Valley, South Napa, Silverado, Highway 29 Trancas.

The percentage of cell sites in the Napa area with generators is substantially higher than in other areas like San Francisco or Oakland; in San Francisco, the ratio is believed to be under 20%. This reflects the difficulties in highly urbanized area of installing permanent standby generator sets. Battery-only backup power will last, typically, only for a few hours, unless the batteries can be recharged.

In Browns Valley, a cell site was located immediately adjacent to the water tank 'B" that was damaged (Figure 4-9). This cell site provides substantial coverage to the Browns Valley area. Verizon connected an emergency generator to provide power, and added CMU cards for additional call capacity. This site suffered minor internal damage (possibly ? due to water that sloshed out of the tank?) but was operating at 100% on battery power until Verizon was able to hook up an emergency generator.

PG&E (see Chapters 3 and 8) mobilized a large repair effort, with a command center next to the Napa County fairgrounds. This high concentration of users at this location, coupled with the overall increase in call volume, caused PG&E to have connectivity issues. PG&E requested Verizon to provide additional capacity. Verizon responded quickly with a Cell on Wheels (COW) to increase coverage and capacity for PG&E's recovery effort.

At one cell site at a local hospital, PG&E power was lost, and the limited capacity of the batteries resulted in a 1.5 hour loss of cell service. PG&E power was restored to this site just as Verizon was about to hook up an emergency generator.

Overall, the Verizon wireless network was severely impacted by the large increase in traffic. This was most readily observed in the 3G and 4G data network. Physical damage was primarily located at a roof top location, with access for repairs compounded by concurrent damage to the 3rd-party building below. With PG&E able to restore power essentially everywhere within a short time frame, and the high ratio of sites with emergency generators, there was only one instance of a cell site going "off the air" due to loss of power, and that was only for a short time.

7.0 Fire Following Earthquake

A survey of fire sites was conducted on the day following the earthquake (August 25, 2014), and data obtained from an interview with senior officers of Napa City Fire Department (NFD). A complete list of incidents the NFD responded to was not available at the time of the interview – fires attributable to the main shock are summarized in Table 7-1.

No.	Time of Report (approx.)	Location	Description (see below)
1	0330	Orchard Ave	Napa Valley Mobile Home Park (NVMHP) – actually two ignitions – see narrative
2	0400	Laurel St. (no street number)	2 story, 2 unit residence, roof collapse, started fire
3	0500	162 Robin at Solano	Dbl wide home
4	0630	1990 Trower	Smoke inside structure
5	0730	770 Lincoln x Soscol	Electrical fire in substructure of a mobile home
6	1200	4072 Rohlffs Way x Fair	Kitchen fire in single story multi-unit senior housing complex

Table 7-1. Fires Attributed to the August 24 2014 Main Shock

Orchard Ave Fire: This was the largest fire in the earthquake. First dispatch was of T1 to a report of gas odor but en route T1 observed a fire in the Napa Valley Mobile Home Park (NVMHP) off of Hwy 29 at Orchard Road, and diverted to this incident. T1 encountered a broken water main spewing water at the entrance to the NVMHP on Orchard Road, and proceeded to enter the NVMHP. T1 then encountered a single structure fire at 313 Mark Way – the structure was 50% involved; they also observed a second fire at 317 Patty Way, which was 100% involved and impinging on neighboring buildings, see Figure 7-2. Wind conditions were calm.

Approximately 20 minutes into the incident (i.e. about 0400) Water Tenders 15 and 25 arrived from Napa County Fire Department. NFD E6 had also arrived and took water from one of the WT 15 and suppressed the Mark Way fire. T1 and WT 25 similarly suppressed the Patty Way fire. Overhauling continued until about 10am.

1990 Trower: This was a report of smoke inside a structure. This site is a restaurant – employees reported some equipment had fallen onto other equipment in the kitchen, causing a call to the fire department. No significant damage occurred.

Rohlffs Way: This was a report of smoke in a kitchen area of a senior citizens residence

Mutual Aid: As reported above, Napa County FD responded quickly with water tenders. By noon, two OES strike teams had arrived in Napa.

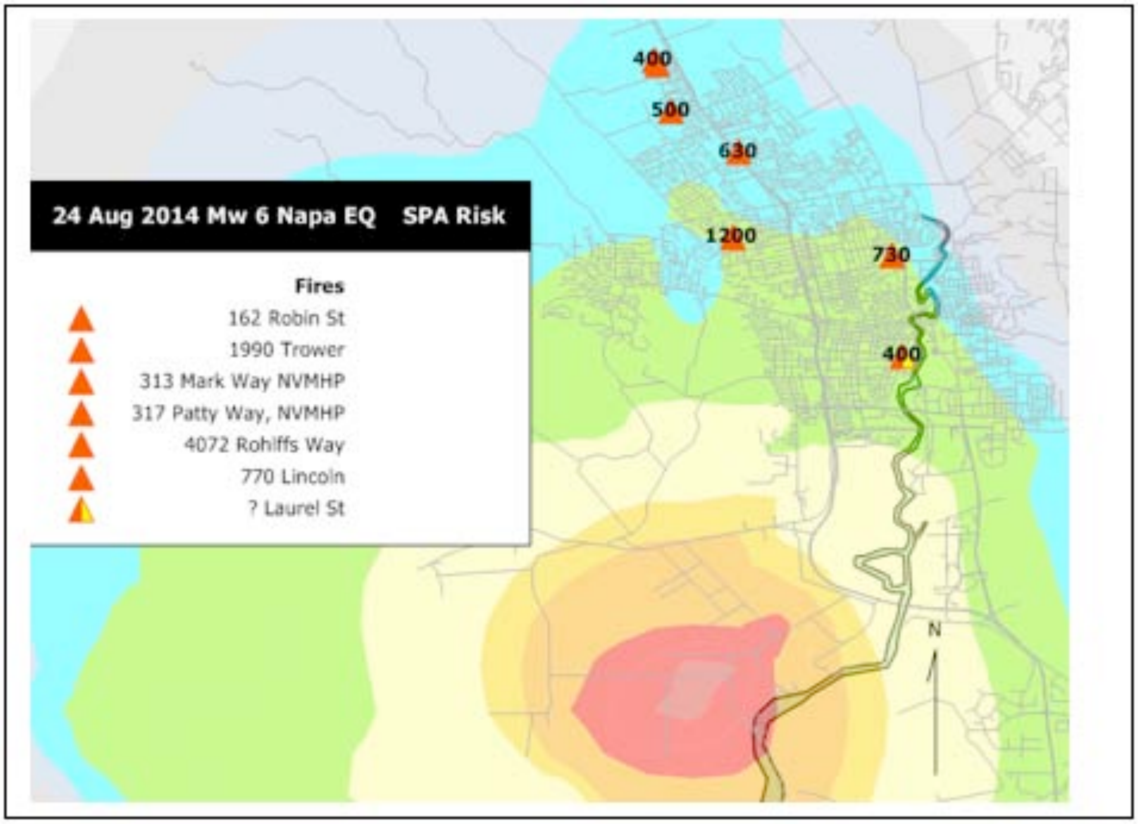


Figure 7-1. Location of Fires in Napa, with Overlay of ShakeMap (v1)

Figure 7-2. NVMHP Park and locations of fires, 24 Aug 2014 S. Napa M_w 6.0 Earthquake (damaged buildings outlined in red)

Table 7-2 lists the rate of ignitions from the Napa earthquake per million square feet of buildings, as compared to horizontal PGA.

No.	PGA Range	Built Inventory, Millions Square Feet	Ignitions	Ignitions / MM sq ft
1	0.5g – 0.6g	7.5	0	0
2	0.3g – 0.5g	50	3	0.06
3	0.15g – 0.3g	40	3	0.075
4	0.05 – 0.15g	15	0	0

Table 7-2. Ignition Rate

Figure 7-3 shows the fire ignition rate from the Napa earthquake along with fire ignition rate data from other recent earthquakes, and various models that correlate the ignition rate versus input PGA. It is apparaent that the Scawthorn model, which relies heavily on the 1906 San Francisco earthquake ignition data, is no longer useful; this reflects that coal- and other fuel fired-cooking over open hearths in brick buildings, and vulnerable gas pipelines, is no longer the norm in most of California (or for that matter, in many other places in the world). If we exclude the data from prior earthquakes where building damgae was primarily in unreinforced masonary buildings (1906 SF, 1983 Coalinga, Long Beach 1933, Santa Clara 1906 (four of the black squares located above the solid black line HAZUS model in Figure 7-3), which is included in the HAZUS model and the Scawthron model), and include the data from recent 2010 – 2014 earthquakes, the lower ignition model (red dashed line) appears to better represent the modern world. The number of structures ultimately burned down is highly dependent on wind, the availability of water, and the availability of enough fire department engines and crews to control many simultaenous fires (Eidinger, 2004). It would appear that modern building (and cooking, etc.) practices have reduced the fire ignition rate, which is one factor to reduce the overall number of burned structures. It also appears that in Napa, the modern water system at the time of the 2014 earthquake) was not much better than the water system that served San Francisco in 1906 – the Napa water department (as of 2014) was still "in the dark ages" of no-seismic design for water pipes.

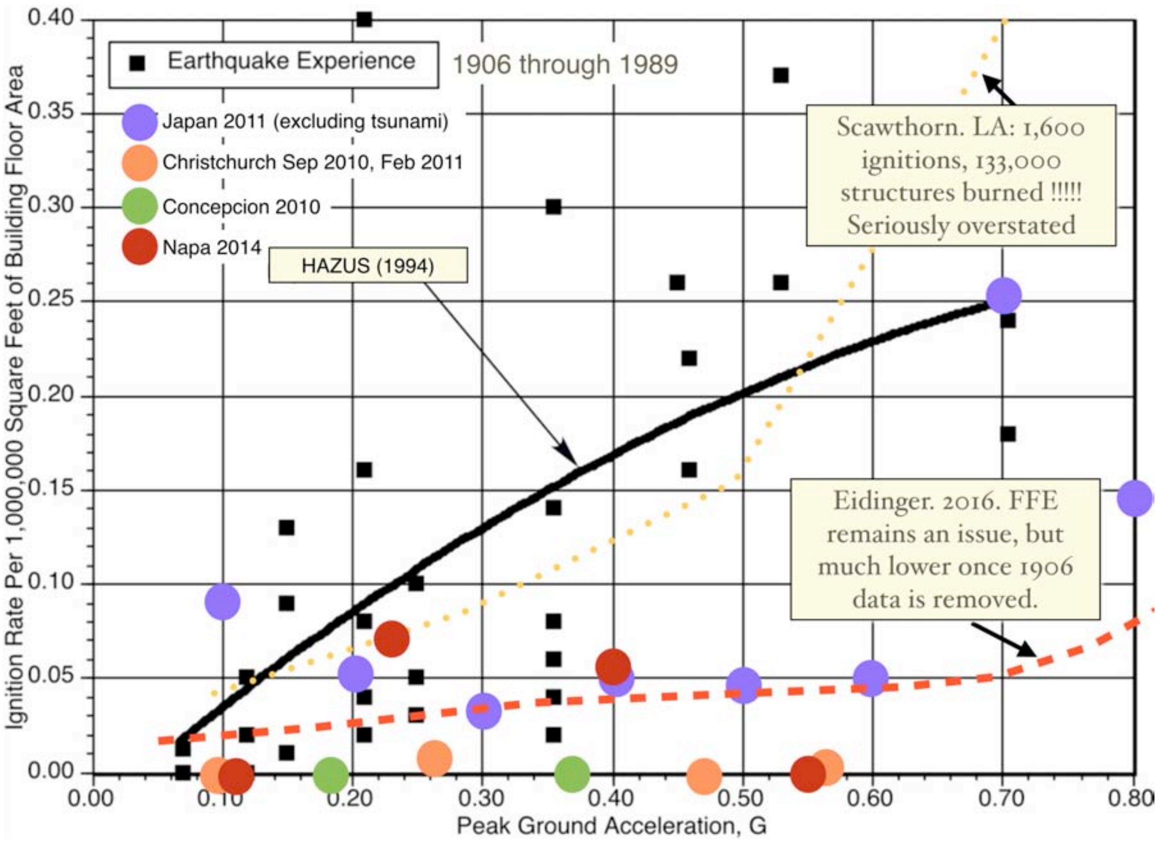


Figure 7-3. FFE Fire Ignition Rate Model

8.0 Gas

Piped natural gas service is provided by PG&E in the urban areas of Napa. In rural areas, gas is provided by local propane tanks.

8.1 Performance of 26 Inch Pipe at Fault Crossing

PG&E operates a 26-inch diameter buried gas transmission pipe (Figure 8-1, Line 021A, welded steel) that crossed the fault (across the dashed yellow line in Figure 2-20). The orientation of the pipe would place it into bending and compression due to the right lateral offset of a few inches (including post-event slip). The pipe remained operational (no leak).

After the earthquake, an estimate was made of the induced strain / stress in this pipe, assuming about 1 foot of offset. It was estimated that the pipe might have sustained a peak bending strain on the order of 0.4% to 0.5%.

By September 1 2014, PG&E uncovered and excavated the pipe through the fault zone, Figure 8-2. The excavated pipe (26 inch outside diameter, 0.297 inch wall thickness, Grade X60 steel, double submerged arc welded seam pipe built 1971, with a maximum allowable operating pressure of 450 psig) was uncovered and examined for indications of anomalies on the body and on the weld seam. No initial indications of pipe wrinkling were found to be present; however, the pipeline was cut out for further evaluation and testing. PG&E ultimately replaced about 200 feet of Line 021A through the fault crossing zone, with 26 inch outside diameter, 0.5 inch wall thickness, Grade X65, SAWL pipe.

This replacement pipe is thought to be more robust than the original pipe, in that is has a lower D/t ration making it more resistant to buckling due to future fault offset; and of course, is installed in a stress relieved state, whereas the 1971-vintage pipe was already loaded due to the fault offset in 2014.

No visually obvious damage was apparent, even after removing the exterior coating. The cut-out pipe was laser scanned for pipe ovality, and girth welds were radiographed and UT phase array inspected for anomalies. As of writing this report, preliminary results conclude that no major integrity concerns were identified such as wrinkling or bending of the pipe.

Figure 8-1. Location of PG&E Gas Pipe Trench Excavation

Figure 8-2. PG&E Gas Pipe Trench Excavation, Sept 1 2014, Looking East

8.2 Other Aspects of the Gas System Performance

The following statistics were provided by PG&E in early December, 2014. The reported quantities below are about 50% higher than the corresponding values known to PG&E within a couple of weeks after the earthquake.

There were about 240 red tagged buildings with loss of PG&E gas service due to damage to the customer facilities.

PG&E responded to 8,600 service "tags" (report of gas odor, leak, safety check…)

PG&E responded to about 2,500 priority 2 calls (safety check, relights, appliance adjustment). Of these, about 35% were in Napa and 4% in Vallejo.

There were 26 priority 0 leaks (reports of blowing gas, with immediate response).

There were 440 non-hazardous leaks detected.

There were 886 non-hazardous meter set leaks.

There were 76 gas pressure regulators in the impacted area, which were inspected. There was no observed damage.

PG&E does not operate seismic shutoff valves on the gas transmission system. PG&E does have automated and remotely controlled valves to enable remote operation. The automated and remotely controlled valves operated as designed during and after the earthquake.

At this time, there is no information on the presence or performance or effect of seismic shut-off gas valves owned by customers.

While there was no leak or apparent damage, PG&E is replacing about 7,000 feet of line 121A. This line uses Aldyl A type pipe. The 7,000 foot reach of this pipe being replaced is in the neighborhood where the fault ruptured the surface of the ground.

Industry experience has identified that Aldyl A pipe that had been manufactured between 1970 and 1972 sometimes has low ductile inner wall characteristics that resulted from excessive temperature settings during the extrusion process (Haine, 2014). These pipes are predisposed to initiate cracks faster on the inner wall. Recognizing this issue, PG&E has adopted a pipe replacement program.

9.0 Other

Broken Glass. There was a 1950's vintage single story wood framed school building at the epicenter and adjacent to the zone of surface rupture. This building (labeled "1958 Building" in Figure 2-23) had hundreds of single pane, annealed glass windows, in wood sashes with putty. About 6 of the panes cracked, with nearly all shards remaining in the sash (not a falling hazard).

Suspended lights. At the same school building, modern suspended lights over classrooms that had been "seismically braced" (using diagonal wires) had many of the diagonal wires pull their anchors out of the adjacent walls (mostly drywall); other lights that had no "seismic braces", being left free to swing, had no damage (and no drops). The prudency and effectiveness of such "seismic bracing" (as mandated by modern codes) appears to be unwarranted in this case.

There was one reported fatality in this earthquake. About 200 people reported to the local area hospital, of which about a dozen were admitted, and the rest out patients. This hospital had sustained some non-structural damage in the Napa M 5.2 earthquake of 2000 (Eidinger et al, 2000), and was serviceable in the Napa 2014 earthquake.

10.0 References

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