Resiliency of Power Grids After Earthquakes

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No Power = No Resiliency

- No power = everyone unhappy
- How long will the power be off? 1 Day? 3 Days? 2 Weeks? Can a power company make a forecast?
- Today, describe the resiliency of the electric system in San Francisco (and Kyushu Electric near Kumamoto)
- New models can now make forecasts.

Questions

- Everybody “knows”, or at least “suspects” that the power will go off after a large earthquake
- Why does the power go off?
- What is the actual damage in the electric system?
- Can the power company restore power to select critical customers within a short time frame (hours? days? weeks?)

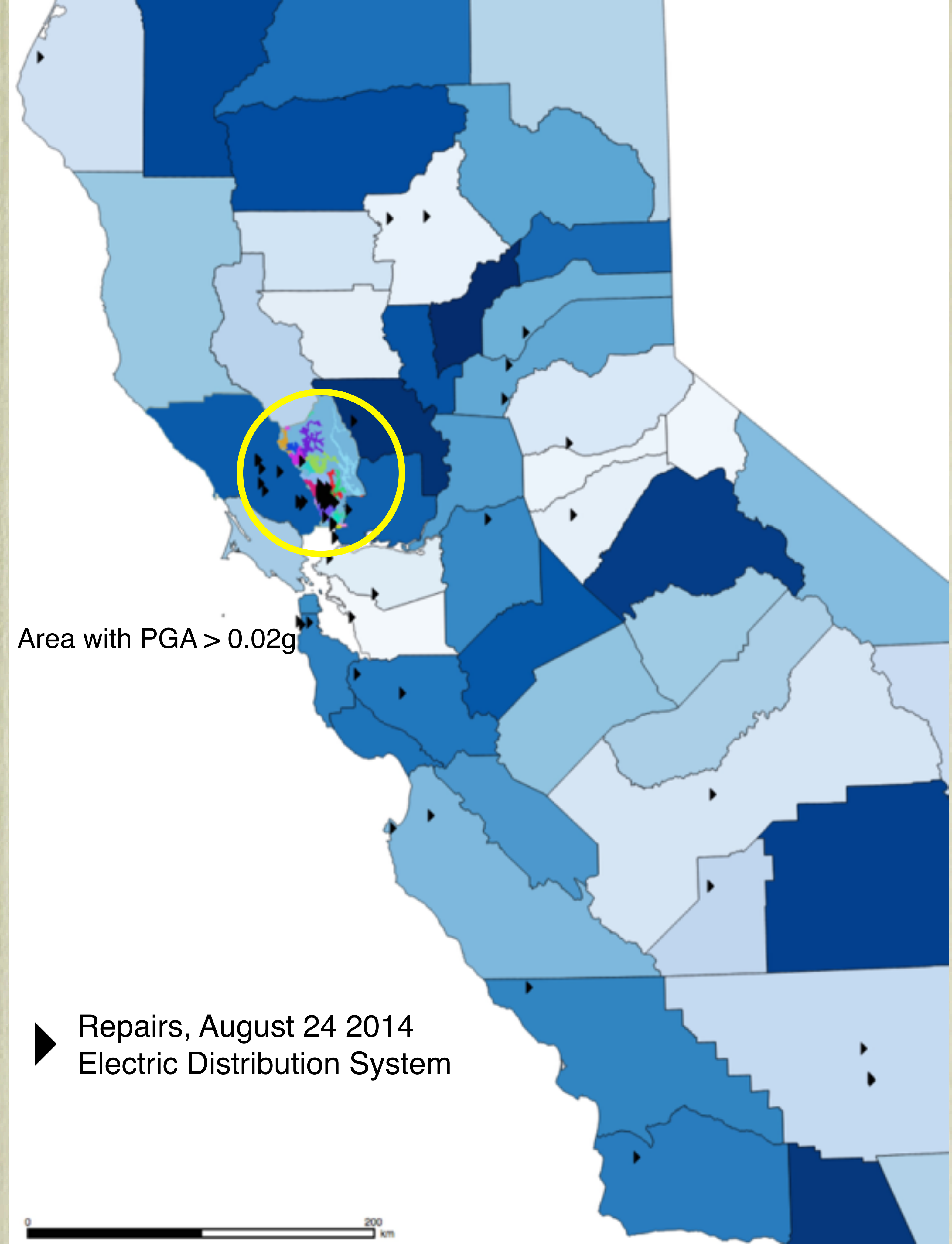
August 24 2014
M 6.0 Napa Earthquake

Power Outages to
70,000 PG&E customers

PG&E serves 15,000,000
people, 5,100,000 customers

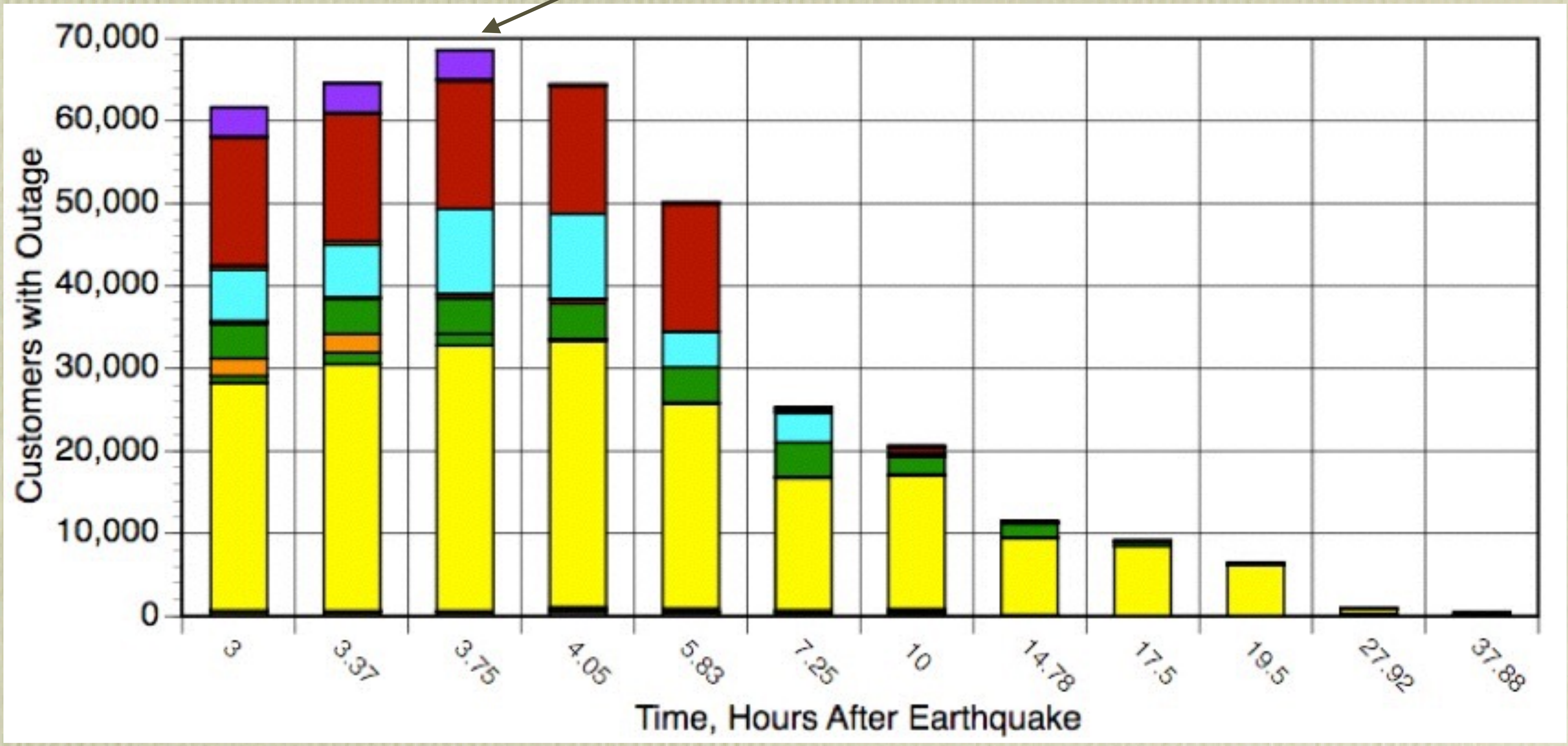
We studied every repair location and PG&E's transmission and distribution networks, and developed "rational" models to forecast power outages.

We then applied this to
San Francisco
for M 6 to M 8 earthquakes
on the San Andreas fault



PG&E Customers without Power

1.4% of PG&E's 5,100,000 Customers



Yellow: Napa
Orange: Rohnert Park
Green: Saint Helena
Cyan: Santa Rosa

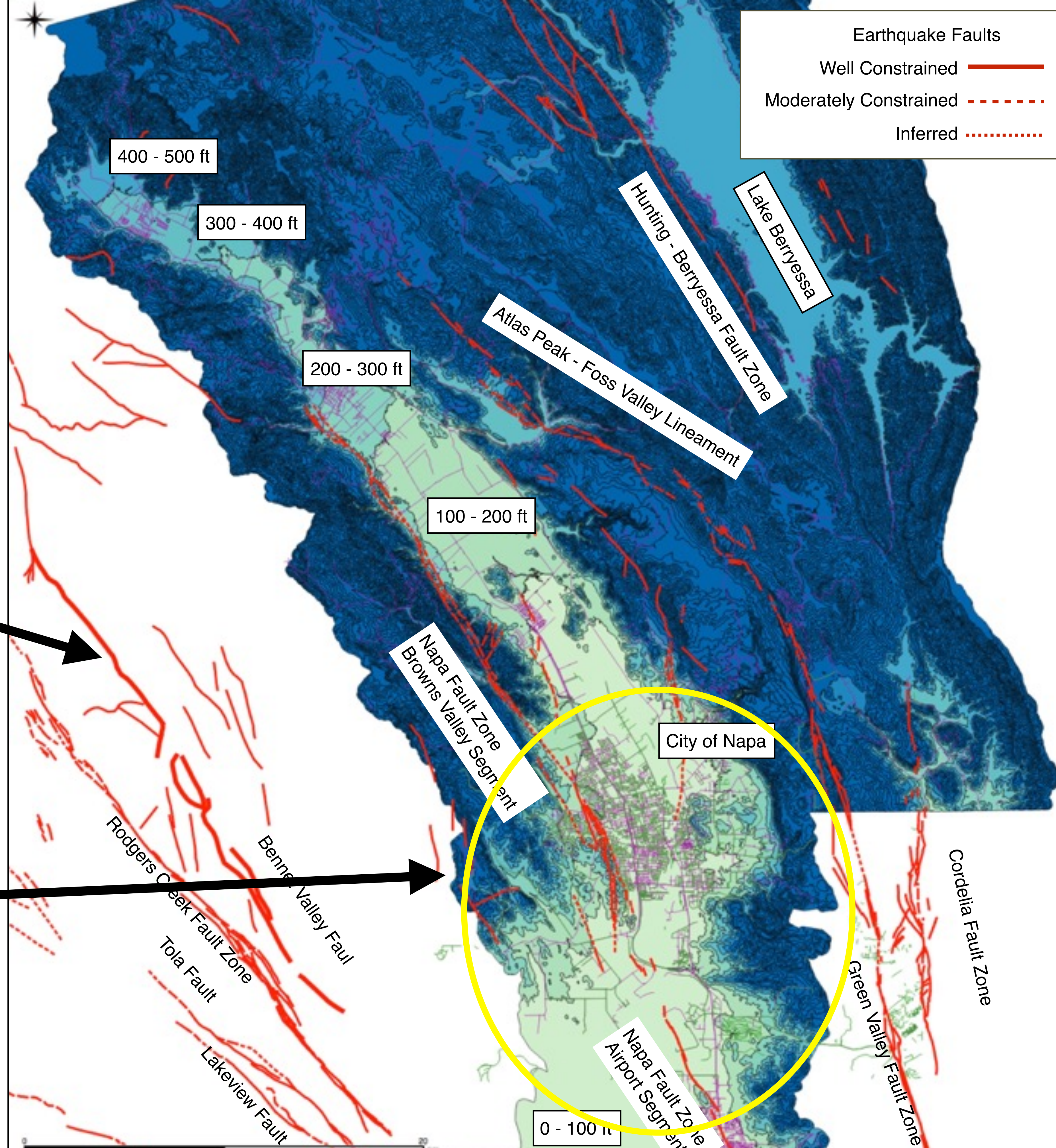
Red: Sonoma Valley
Grey: American Canyon
Blue: Vallejo

~7,000,000,000,000 grapes

Napa Valley

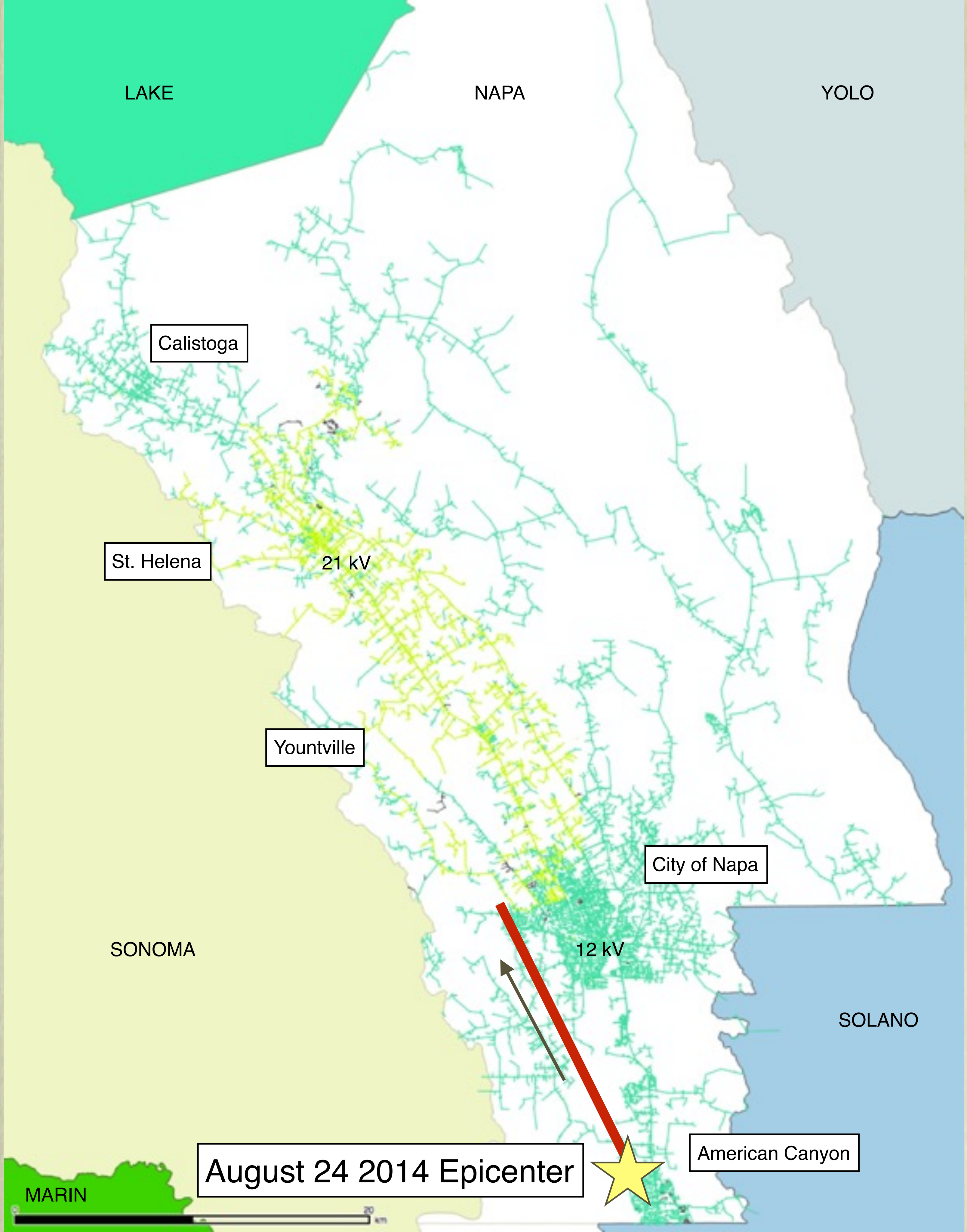
Many earthquake faults

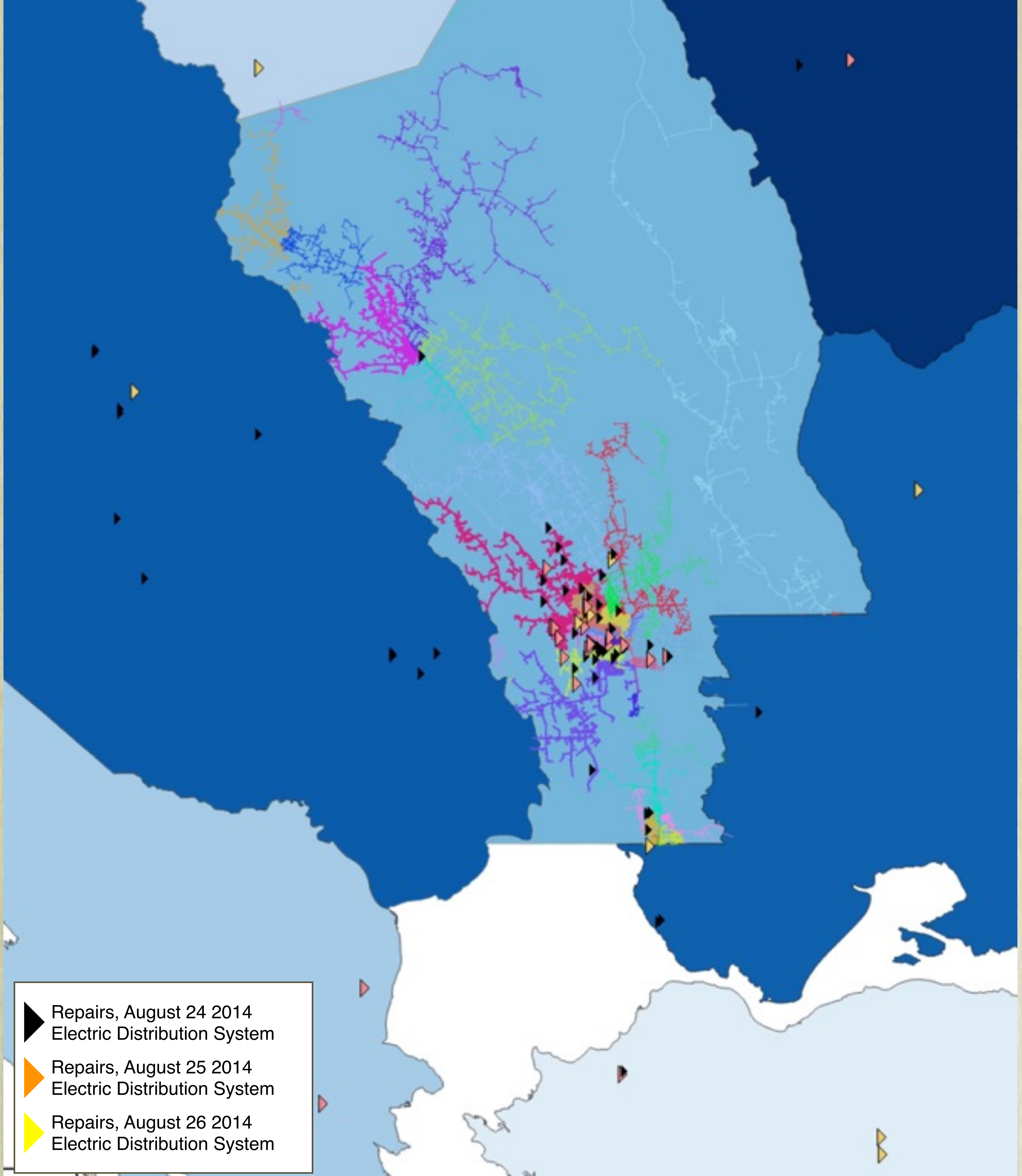
Area with strong shaking.



Objective:

How to include damage to distribution systems to forecast power outages in future earthquakes




Repairs, August 24 2014
Electric Distribution System
Repairs, August 25 2014
Electric Distribution System
Repairs, August 26 2014
Electric Distribution System

Types of Damage

- Napa 2014 Earthquake.
- 127 damage locations.
- 23 “types” of damage.
- Most common (53%) is overhead conductors; then overhead cross arms and overhead jumpers.
- No broken poles.


Repairs, August 24 - 30 2014
Electric Distribution System
Overhead
Underground
0
4
km

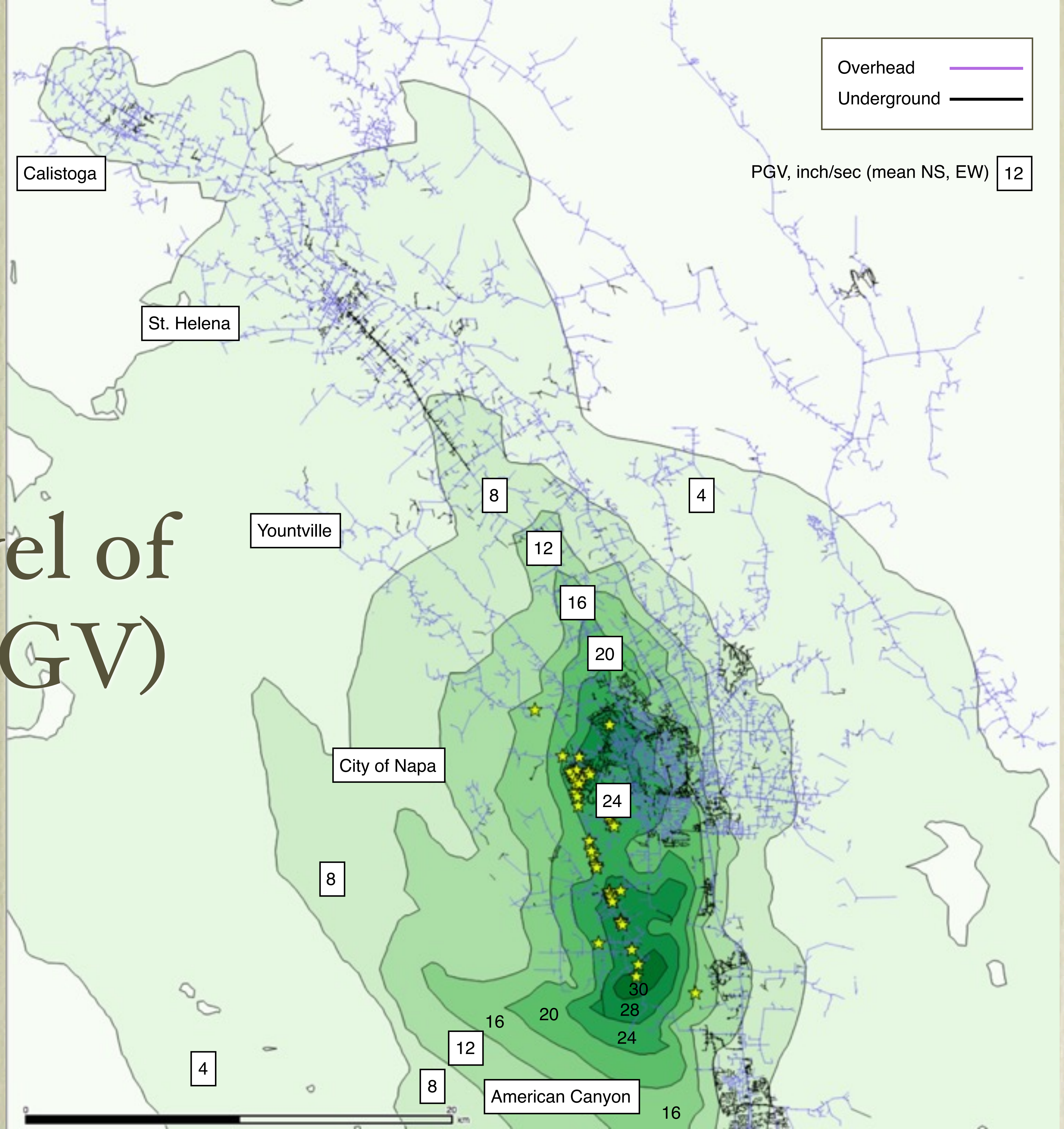
Type of Damage	Earthquake	Non-Earthquake	Total
Anchor		5	5
Capacitor		2	2
Conductor	68	199	267
Conduit		1	1
Connector	4	34	38
Cross Arm	12	36	48
Cutout	3	18	21
Enclosure			
Enclosure, Lid, Frame	1	21	22
Guy	6	5	11
Guy Marker		2	2
Hardware / Framing	3	7	10
Insulator	3	8	11
Jumper	8	14	22
Other		16	16
Pole		57	57
Switch / J-Box	1	6	7
Tie Wire	2	4	6
Transformer, Regulator Booster (OH)	8	70	78
Transformer Pad mount (UG)	2	30	32
Transformer Subsurface (UG)	2	11	13
Tree Fell , Tree, Vince Clearances		7	7
Unknown	4		4
Total	**127**	**553**	**680**

Type of Damage	Earthquake OH	Earthquake UG	Total
Anchor			
Capacitor			
Conductor	65	3	68
Conduit			
Connector	4		4
Cross Arm	12		12
Cutout	3	1	4
Enclosure, Lid, Frame			
Guy	6		6
Guy Marker			
Hardware / Framing	3		3
Insulator	3		3
Jumper	8		8
Other			
Pole			
Switch / J-Box		1	1
Tie Wire	2		2
Transformer, Regulator Booster (OH)	8		8
Transformer Pad mount (UG)		2	2
Transformer Subsurface (UG)		2	2
Unknown	2	2	4
Total	**116**	**11**	**127**

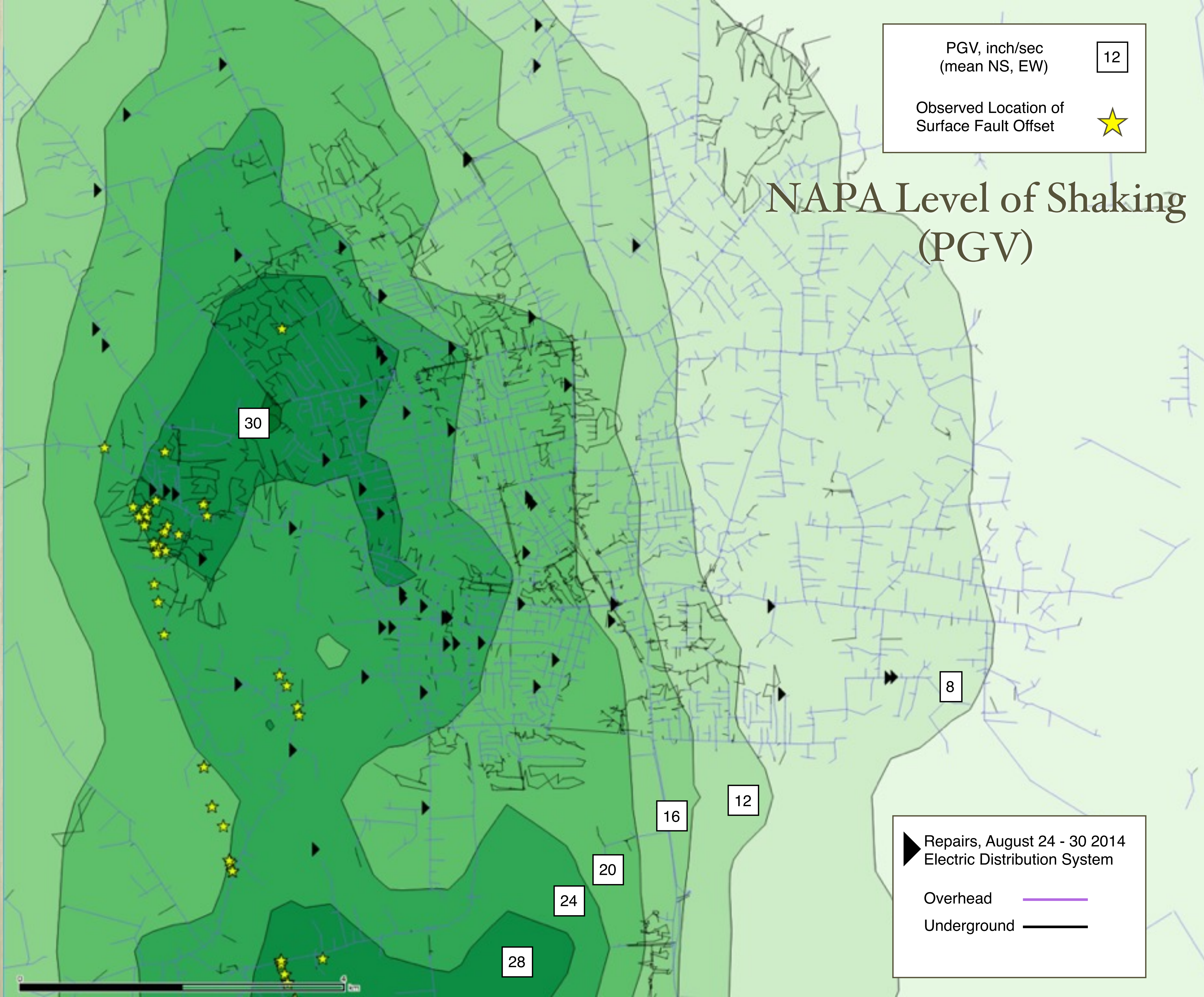
NAPA Distribution Damage

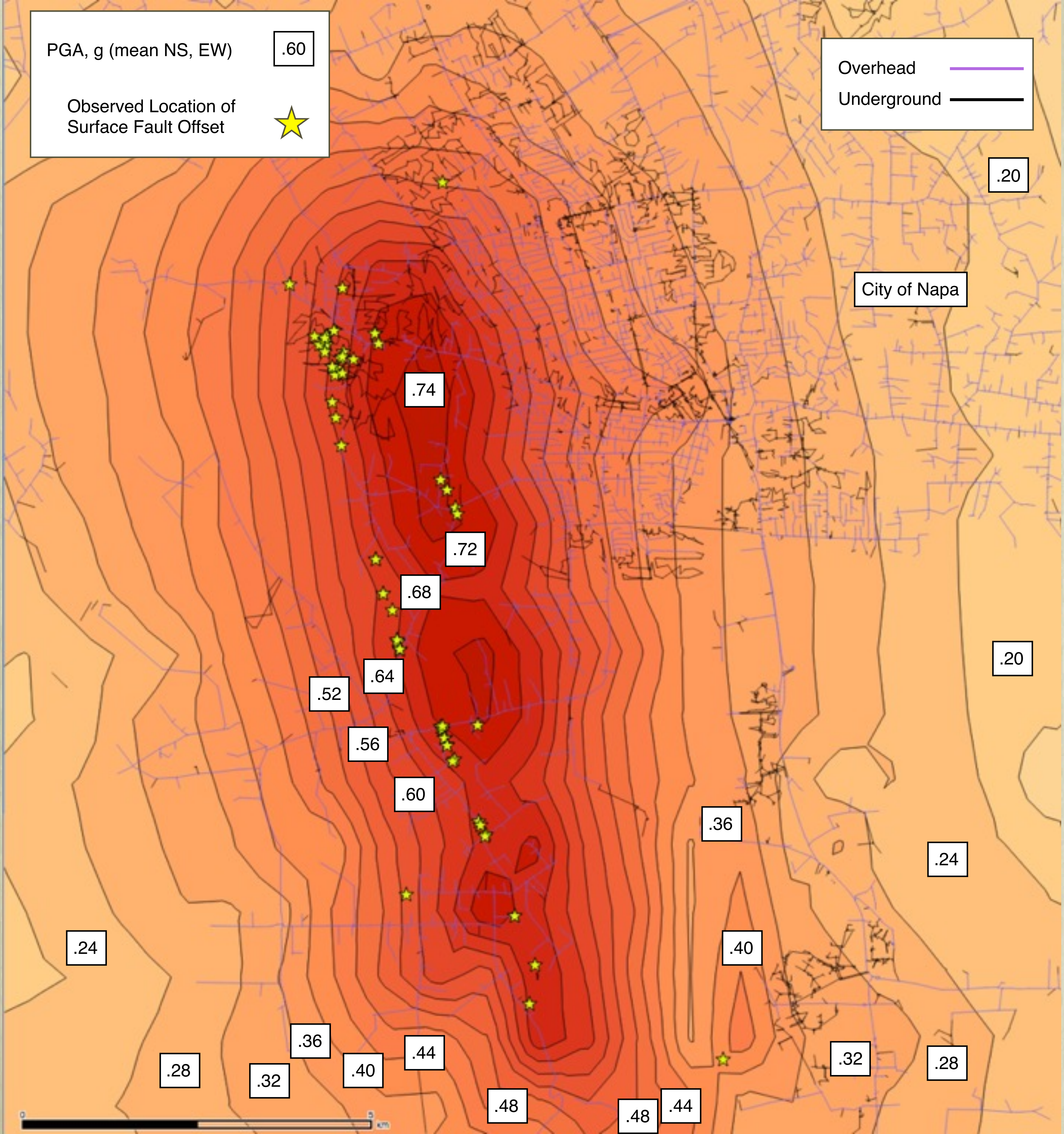
Repair Item	Total Manhours	Number of Repair Items	Average Manhours per Repair Item
Conductor	1147	68	17
Connector	42	4	11
Cross Arm	247	12	21
Cutout	41	3	14
Enclosure, Lid, Frame	24	1	24
Guy	45	6	8
Hardware / Framing	34	3	11
Insulator	42	3	14
Jumper	81.5	8	10
Switch / J-Box	21	1	21
Tie Wire	25	2	12
Transformer, Regulator Booster (OH)	630	8	79
Transformer Pad mount (UG)	28	2	14
Transformer Subsurface (UG)	71	2	36
Logistics	2000	4	500
Grand Total	4478.5	127	35

NAPA Level of Shaking (PGV)



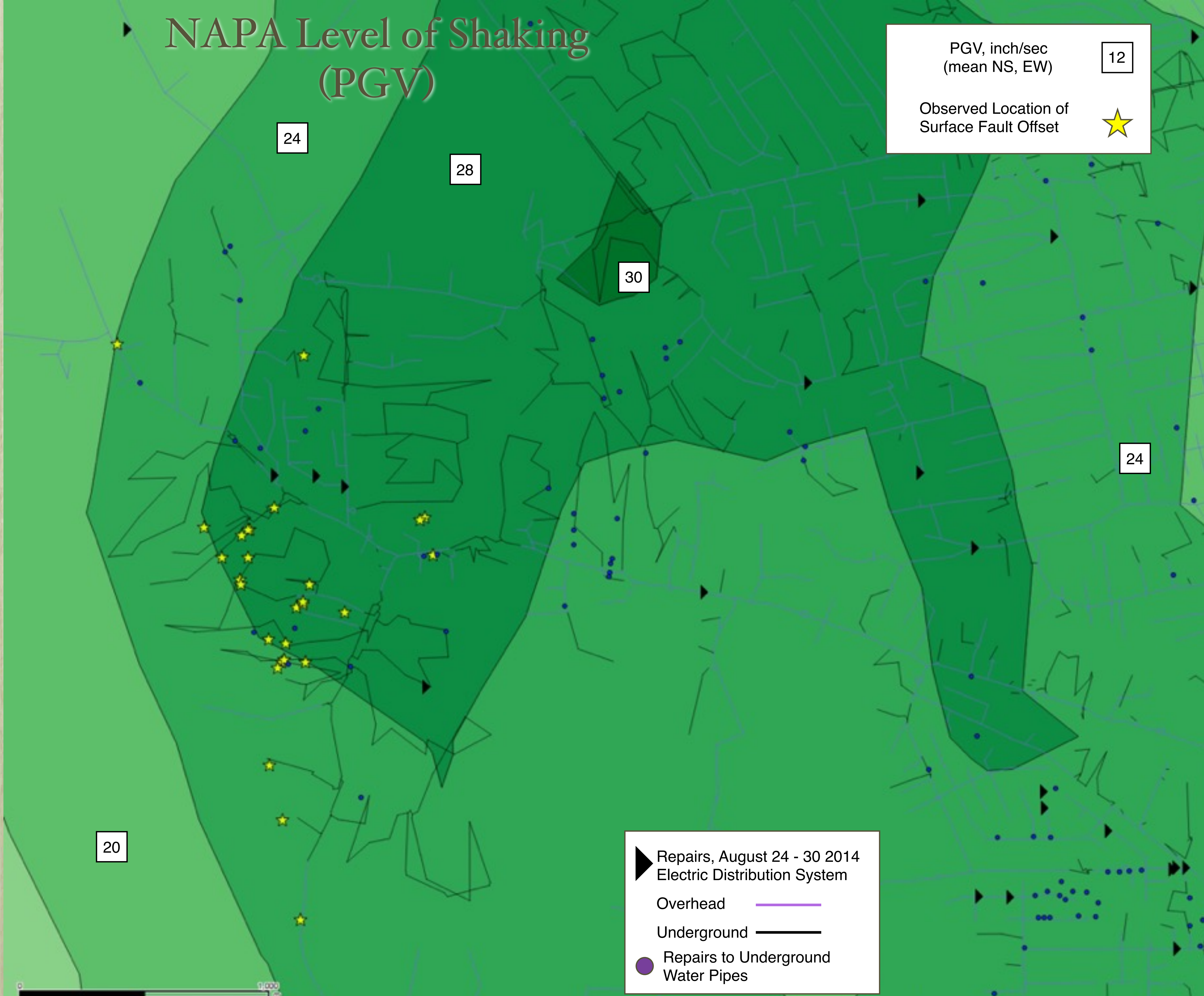
NAPA Level of Shaking (PGV)





NAPA Level of Shaking (PGA)

NAPA Level of Shaking (PGV)



Form of Fragility Models

$$Damage = \sum overhead \;\; damage + underground \;\; damage$$

US, JAPAN, NZ, CANADA *JAPAN*

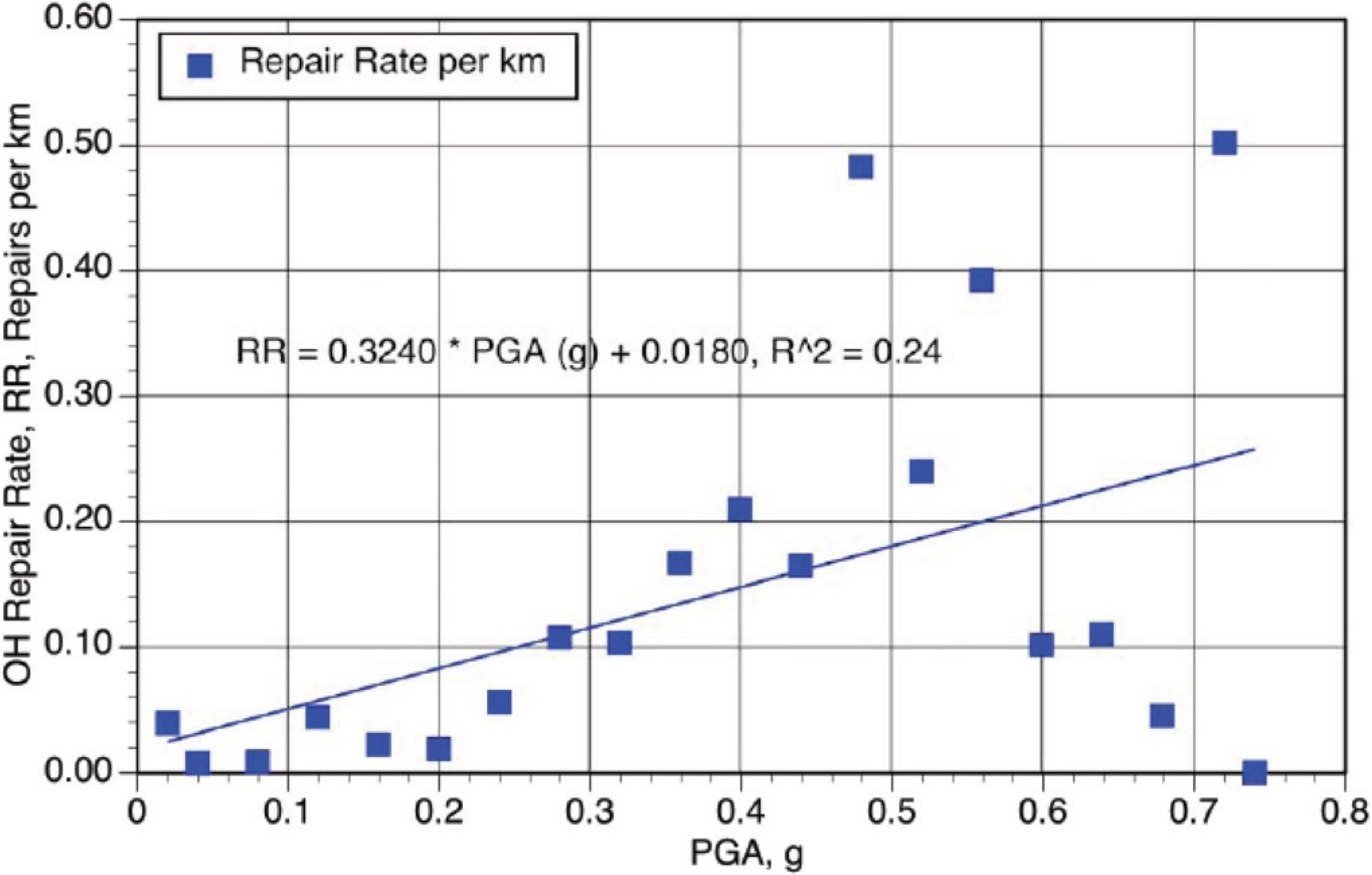
$$Overhead \;\; damage = SUM\left[inertial, \;\; PGD\right]$$ *+ Pulldowns*

$$Underground \;\; damage = SUM\left[inertial, \;\; PGD\right]$$ *+ Pulldowns*

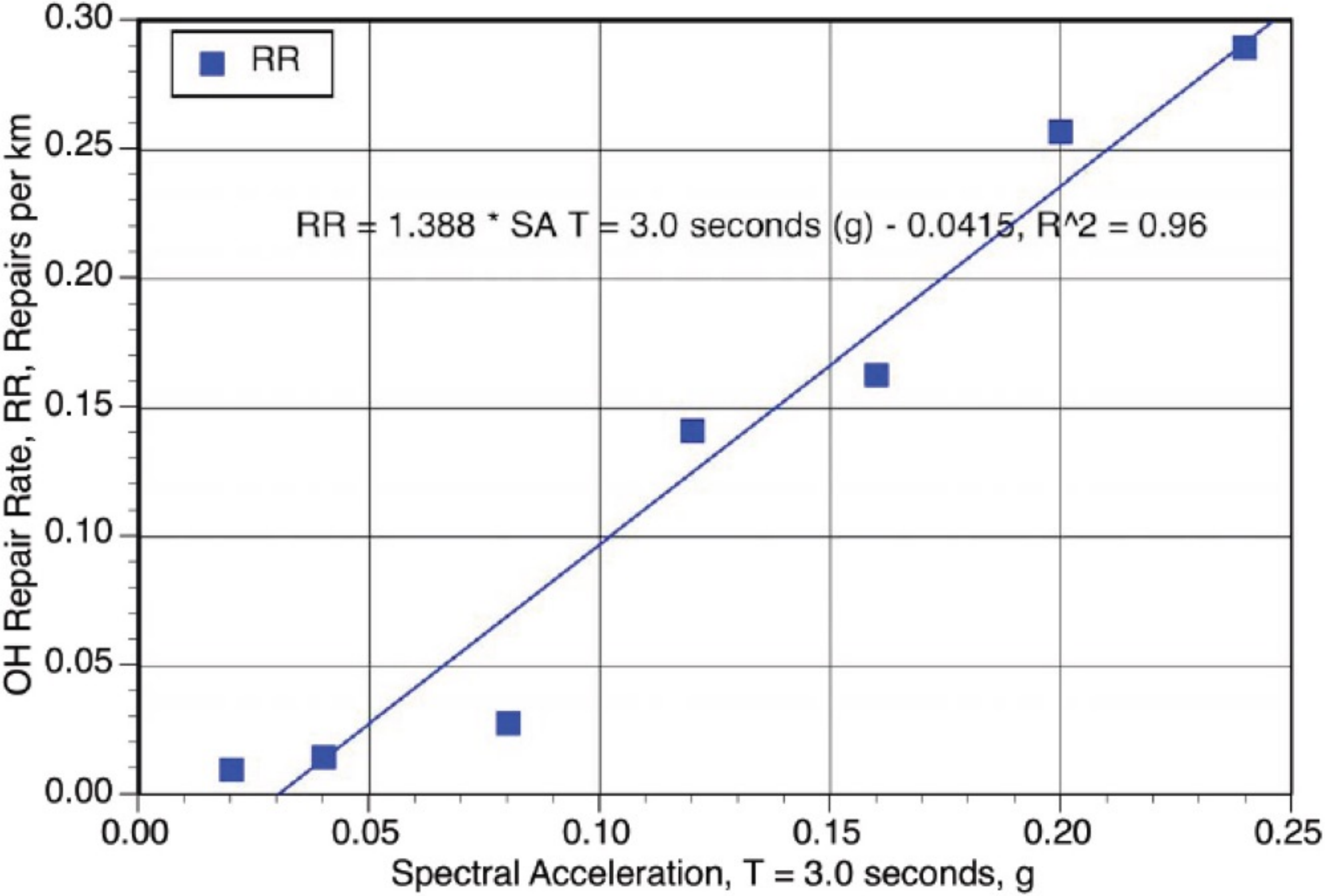
Inertial: damage due to ground shaking (long period motion)

PGD: Permanent Ground Deformations (PGDs)
PGDs are due to Liquefaction, Landslide, Surface Faulting

Pulldowns. Damager to secondaries due to collapse of adjacent structures
JAPAN: This failure mode was very common in Kobe 1995.
NAPA (US): No such failures



Repair Rate per km
RR = 0.3240 * PGA (g) + 0.0180, R^2 = 0.24
OH Repair Rate, RR, Repairs per km
PGA, g
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8



RR
RR = 1.388 * SA T = 3.0 seconds (g) - 0.0415, R^2 = 0.96
0.30
0.25
0.20
0.15
0.10
0.05
0.00
OH Repair Rate, RR, Repairs per km
0.00
0.05
0.10
0.15
0.20
0.25
Spectral Acceleration, T = 3.0 seconds, g

Ground Shaking Fragility Model

Overheads

$$RR_{shake} = k1 * k2 * k3 * k4 * (1.388 * SA_{30} - 0.0415),\ SA_{30} \geq 0.03g$$
$$RR_{shake} = 0.0,\ SA_{30} < 0.03g$$

or, if SA(30) is not available:

$$RR_{shake} = k1 * k2 * k3 * k4 * (0.0111 * PGV - 0.0366),\ PGV \geq 3.3\ \ inch/sec$$
$$RR_{shake} = 0.0,\ PGV < 3.3\ \ inch/sec$$

where RR(shake) is repairs per km and k1, k2, k3, k4 are from Table 4-19.

Underground

$$RR_{shake} = k1 * k2 * k3 * k4 * 0.00187 * PGV,\ inch/sec$$

RR is repairs per 1,000 feet

Case	k1	k2	k3 (age)	k4 (not used)
1. Pre 1960 overhead primaries with overhead secondaries	1.0	1.0	0.8 to 1.25	1.0
2. Post 1960 overhead primaries with underground secondaries	1.0	0.75	0.8 to 1.25	1.0
3. Underground in non-filled duct	0.3	1.0	1.0	1.0
4. Underground in filled duct	1.0	1.0	1.0	1.0

Table 4-19, Repair Rate, due to Shaking

k1 = 1.0 for overhead construction with overhead secondaries. PG&E did not provide us with information about secondaries. Based on visual observations, we estimated that if the overhead circuit was installed 1960 or earlier, it was likely to have overhead secondaries; post-1960, the secondaries are assumed to be buried.

k2 = 1.0 for overhead secondaries.

k3 = 1.25 if year of construction is 1945 or earlier; 1.0 if 1946 to 1990; 0.80 for 1991 or later. For overheads, the k3 factor is thought to be a reasonable proxy for the age-related effects on wood pole and cross arm strength owing the cumulative effects of termites and wood rot. For undergrounds, the incremental strains due to shaking are assumed to not have an age-related effect.

PGD Fragility Model

$$RR_{liq} = k1 * k2 * k3 * k4 * PGD^{1.1245}, \; PGD > 0.5 \; inches$$

$$RR_{liq} = 0, \; PGD < 0.5 \; inches$$

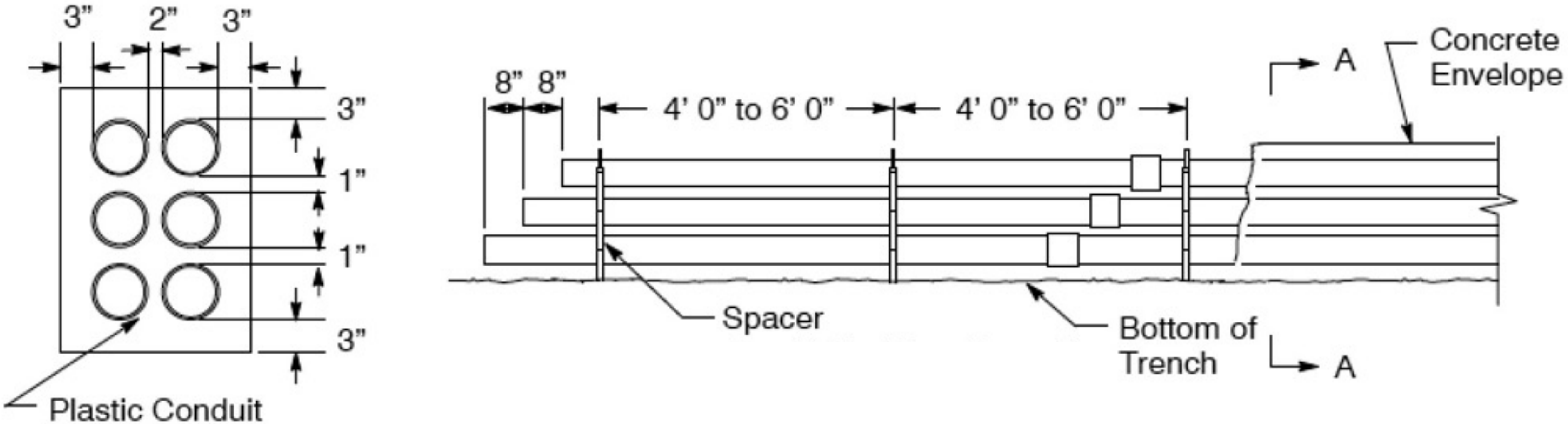
where RR(liq) is repairs per 1,000 feet, and PGD is in inches.

Case	k1	k2	k3 (age)	k4 (not used)
1. Pre 1960 overhead primaries with overhead secondaries	0.00125	1.0	0.8 to 1.25	1.0
2. Post 1960 overhead primaries with underground secondaries	0.0025	1.0	0.8 to 1.25	1.0
3. Underground in non-filled duct	0.01	1.0 unreinforced 0.125 reinforced	0.8 to 1.25	1.0
4. Underground in filled duct	0.026	1.0 PILC 0.80 XLPE 0.80 EPR	0.8 to 1.25	1.0

Fragility Model - PGD

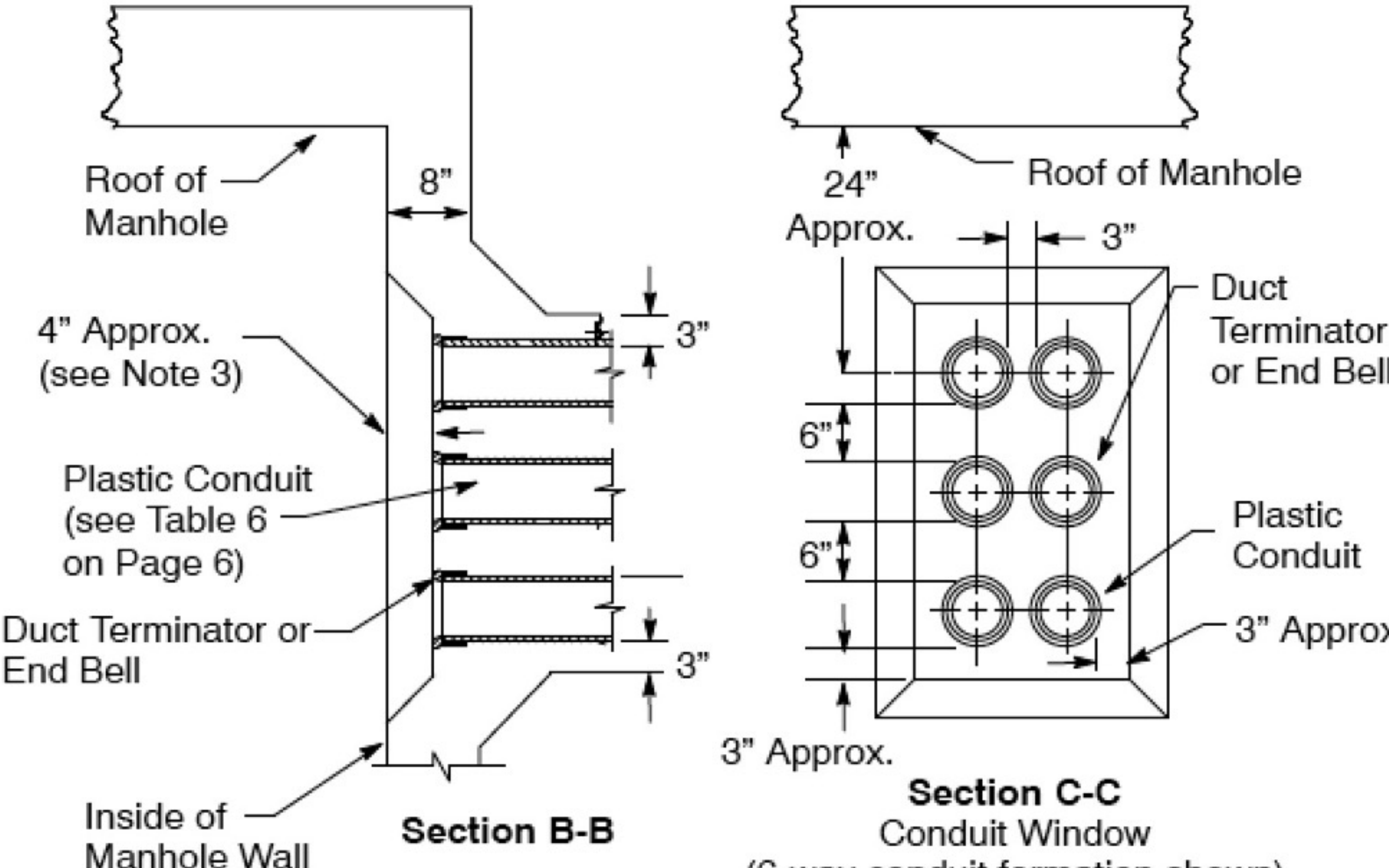
- Key points:
  - Cables in empty ducts, with a little slack, can sustain 10 to 20 cm of PGD with only very rare failures. (But, PGDs > 1 meter are still a problem)
  - Cables in filled ducts, or in direct burial, or in thermal concrete, and much more sensitive to PGDs. >450 buried cable failures in Christchurch in 2011!! Don't build like this in liquefaction zones!

This design can sustain 10 to 20 cm of PGD



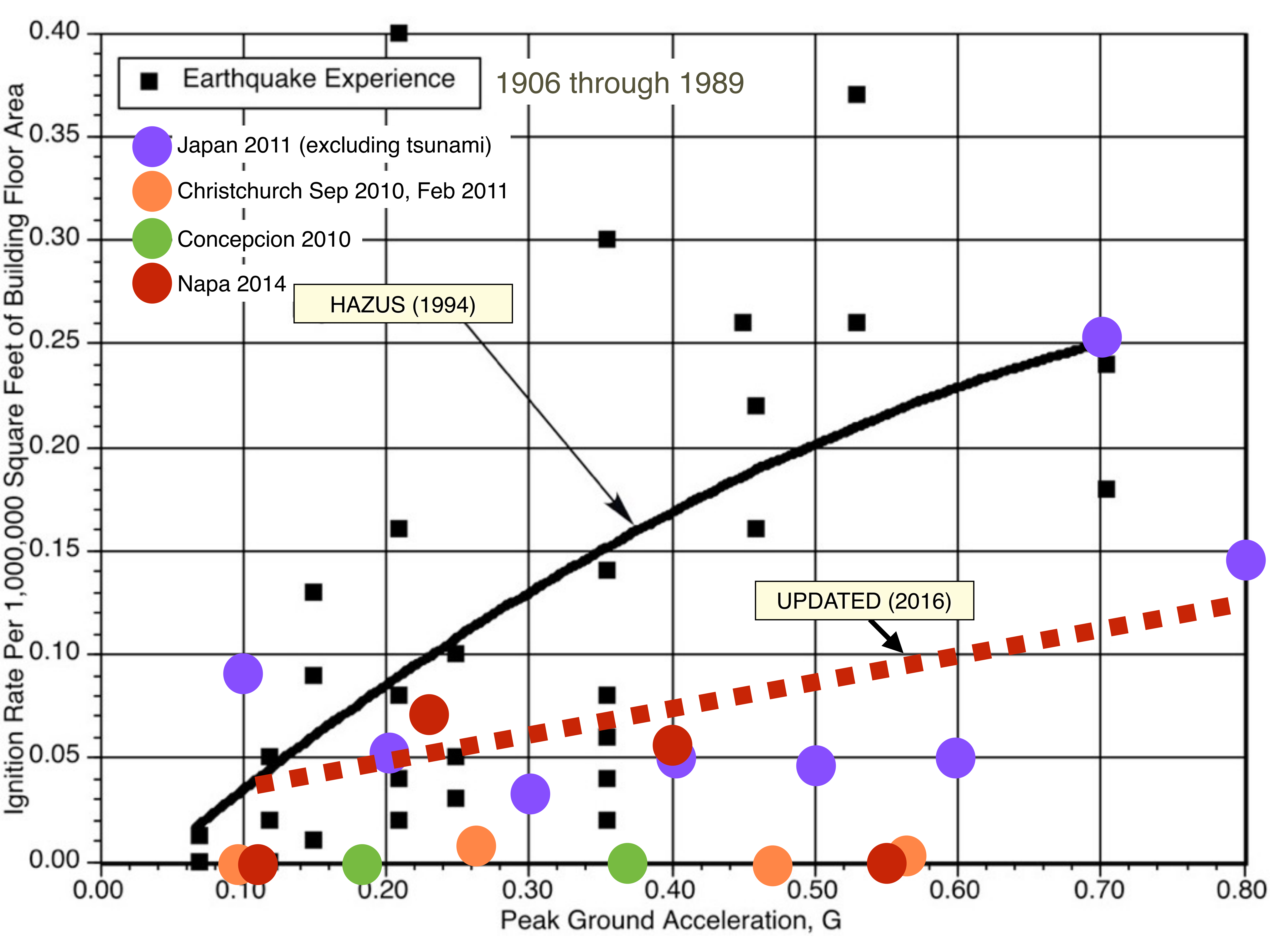
Section A-A

Typical Straight Run Installation (5" conduit, 6-way shown)



Section B-B

Section C-C
Conduit Window
(6-way conduit formation shown)

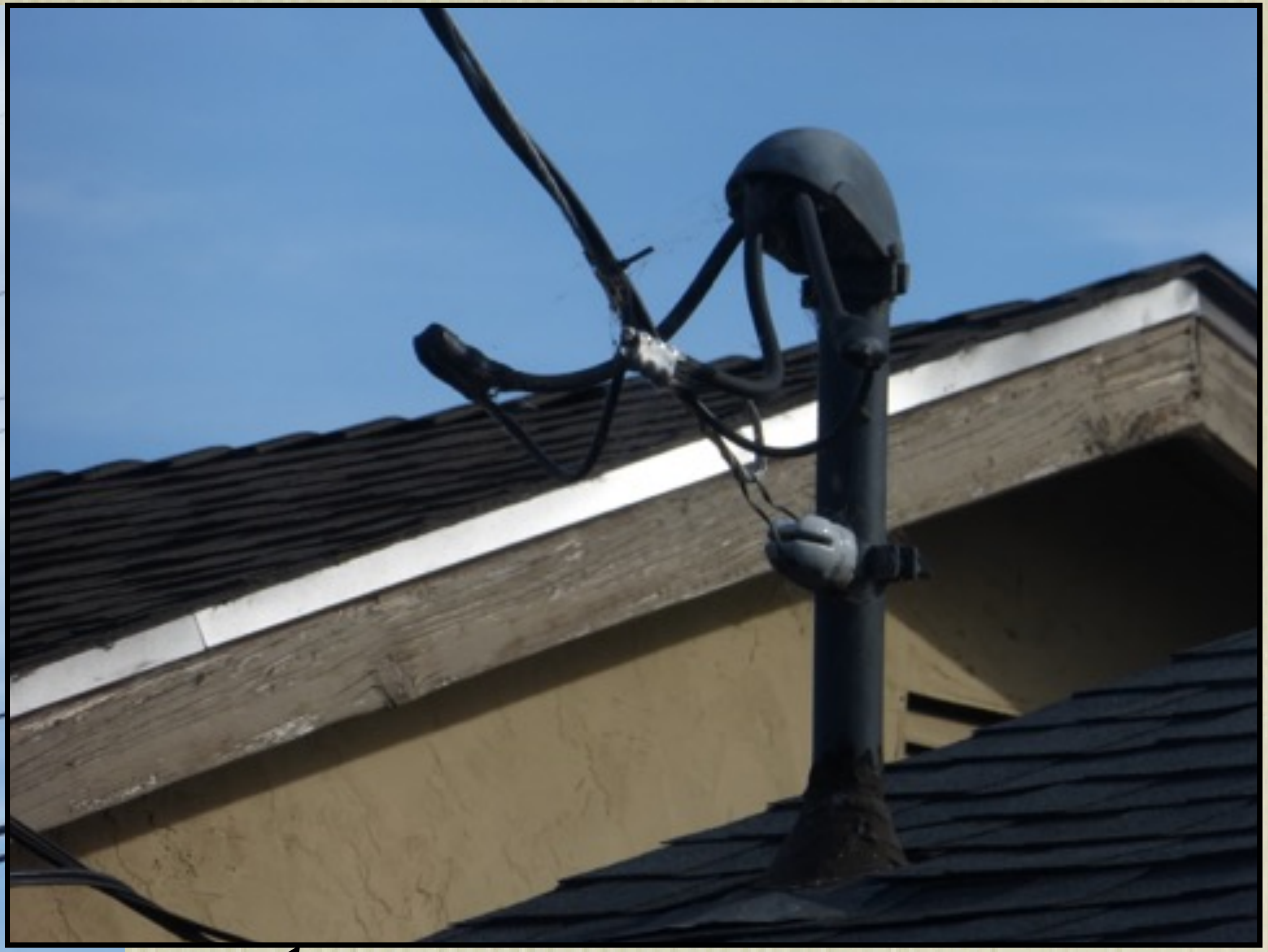


Earthquake Experience
1906 through 1989
Japan 2011 (excluding tsunami)
Christchurch Sep 2010, Feb 2011
Concepcion 2010
Napa 2014
HAZUS (1994)
UPDATED (2016)
Ignition Rate Per 1,000,000 Square Feet of Building Floor Area
Peak Ground Acceleration, G
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.00
0.10
0.20
0.30
0.40
0.50
0.60
0.70
0.80

How Long are the Power Outages?

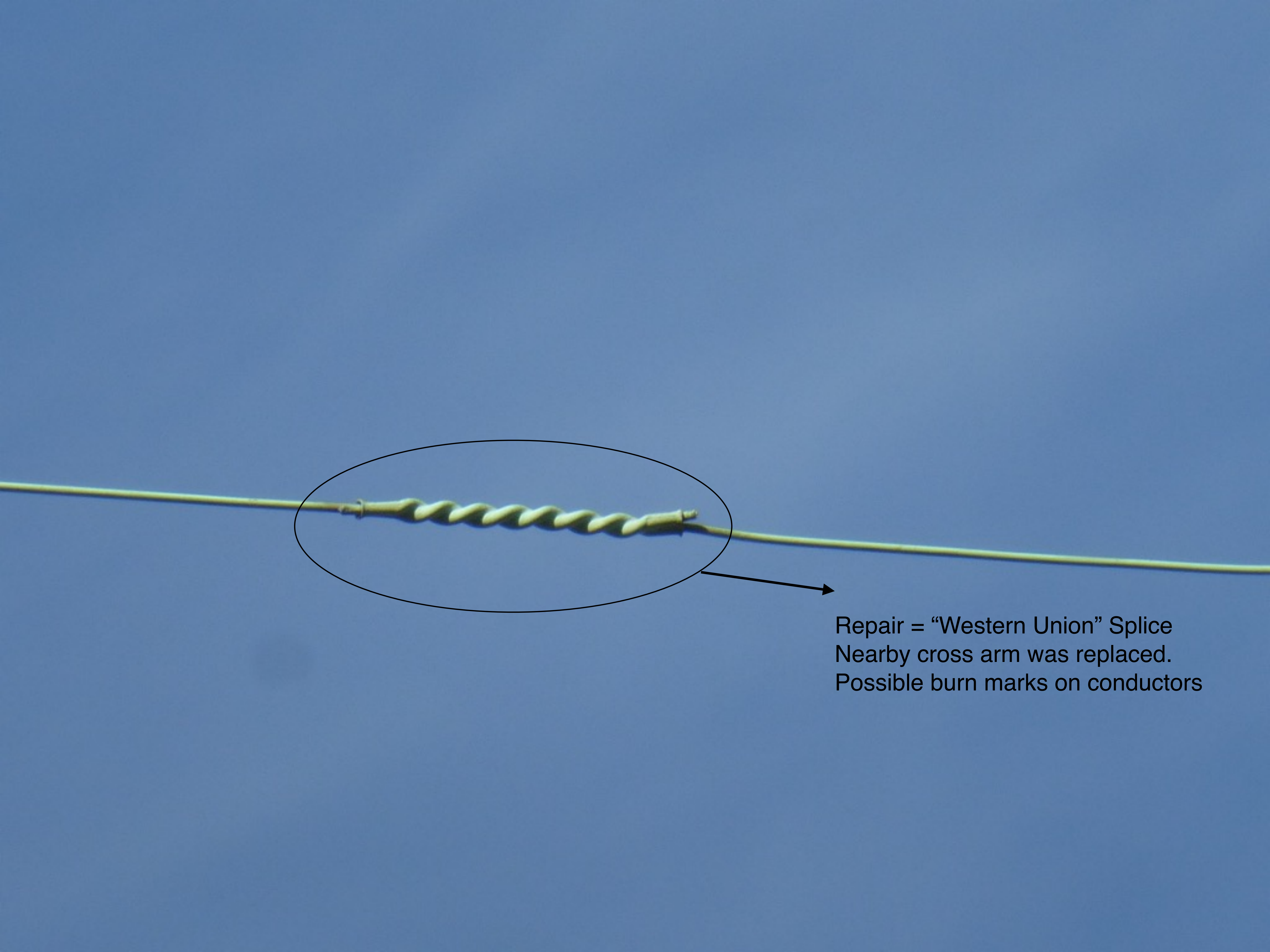
NAPA Power Outages

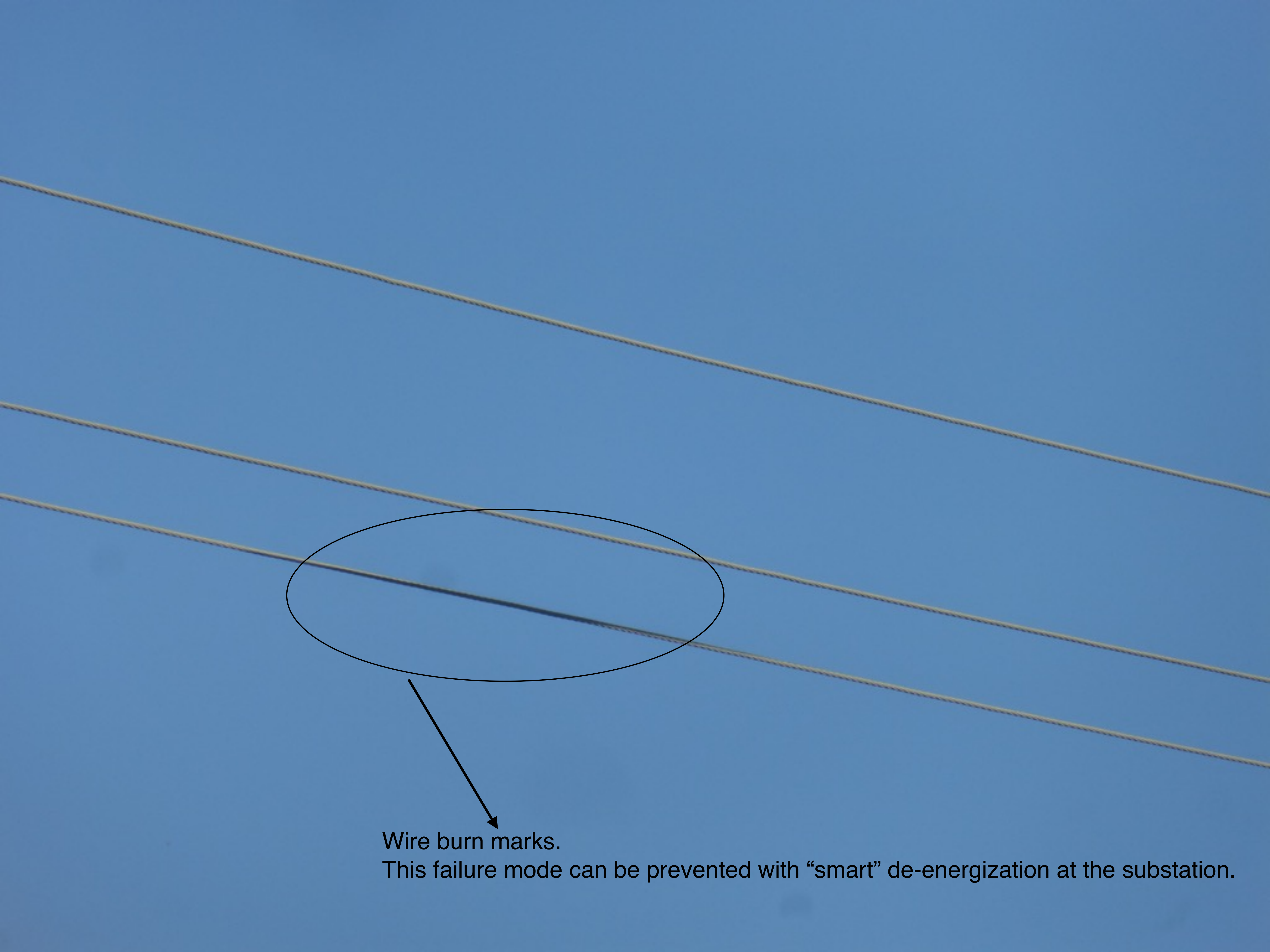
- High Voltage Transmission. Most had been seismic upgraded between 2000 and 2012, many $millions. **No material damage. No outages**.
- Low Voltage Distribution. Pretty good performance (**127 repairs, 37 hour restoration**). Why? Lessons learned in 1952 led PG&E to modify the way transformers are attached to wood poles: all through bolted, none on cross arms, none resting on platforms. Big repair crew (nothing else happening).



Swaying of pole and inadequate slack on secondary line drop to house led to failure of the insulator connection on the house.

Repair = “Western Union” Splice
Why? High Cable Snapping forces lead to damage to the top cross arm, requiring two new fuses /cut-outs.
Fuses were replaced


Repair = “Western Union” Splice
Nearby cross arm was replaced.
Possible burn marks on conductors

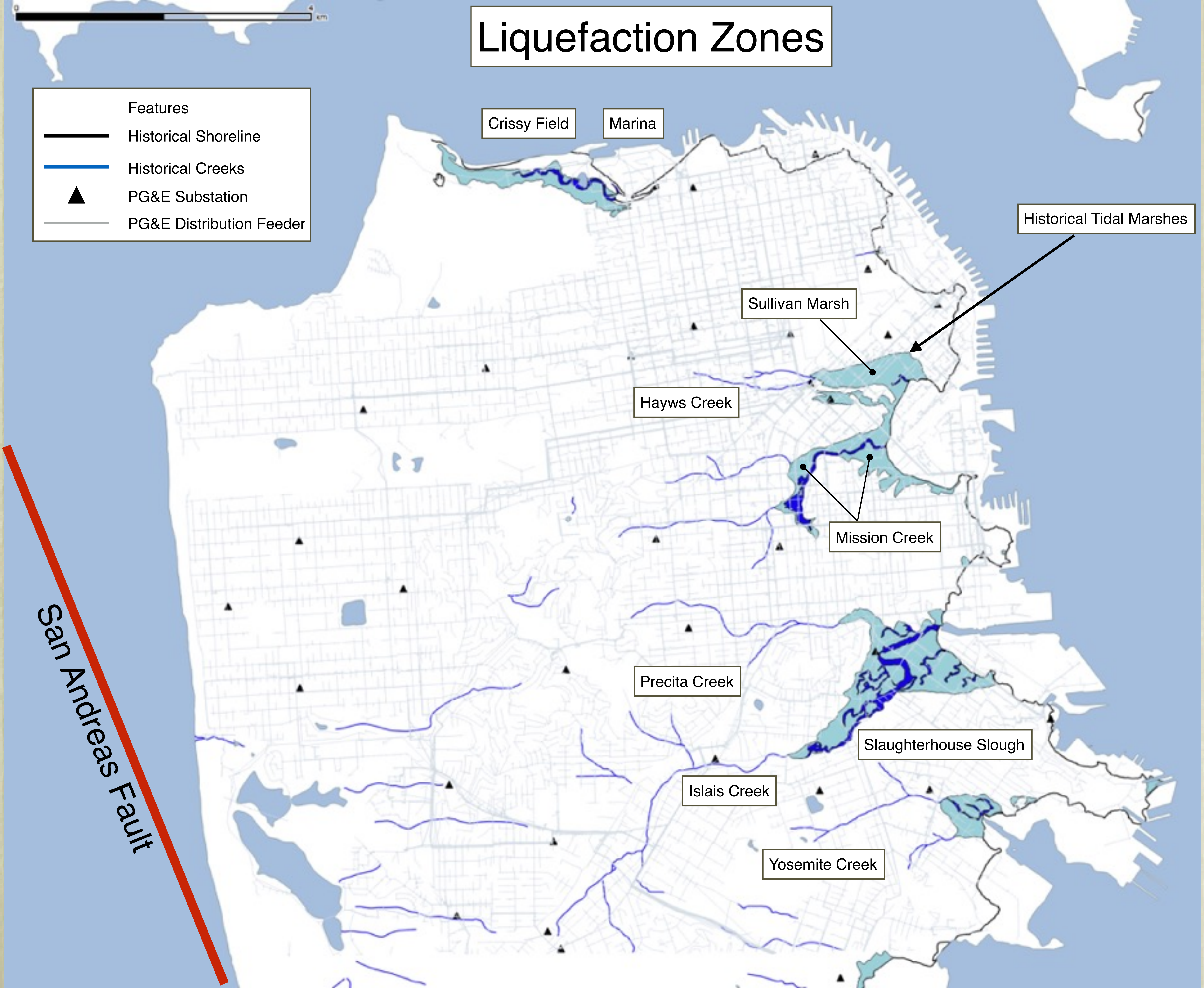

Wire burn marks.
This failure mode can be prevented with “smart” de-energization at the substation.

This cross arm was damaged due to unbalanced “snap” loads.

This one was left in service, but it is damaged and will more easily break in future storms.

Other cross arms had to be replaced.

Liquefaction Zones



San Francisco Damage Forecast

Fault / Segment	M	Shaking	Liquefaction	Landslide	Total
San Andreas SAP	6.0	1.9	0.0	0.0	1.9
San Andreas SAP	6.2	5.3	0.0	0.0	5.3
San Andreas SAP	6.4	13.3	0.0	0.0	13.3
San Andreas SAP	6.6	25.8	0.3	0.0	26.1
San Andreas SAP	6.8	45.4	2.3	0.0	47.7
San Andreas SAP	7.0	77.3	6.4	0.1	83.8
San Andreas SAP	7.2	116.2	13.7	0.2	130.1
San Andreas SAP	7.4	132.6	22.2	0.3	155.1
SA SAN+P+S	7.5	139.3	28.4	0.4	168.1
SA SAN+P+S	7.7	153.1	47.3	1.4	201.8
SA SAN+P+S	7.8	160.2	60.6	2.1	222.9
SA SAN+P+S	8.0	175.0	97.0	4.3	276.3
SA Repeat 1989	7.0	1.6	0.0	0.0	1.6
Hayward N+S	7.5	36.6	4.5	0.0	41.1

Number of repairs to distribution system

San Francisco Power Outage Forecast

EQ No.	Fault / Segment	M	Customer Outages, Median	Percent Outages Median
1	San Andreas SAP	6.0	2,178	0.5%
2	San Andreas SAP	6.2	6,207	1.5%
3	San Andreas SAP	6.4	16,233	4.0%
4	San Andreas SAP	6.6	32,137	8.0%
5	San Andreas SAP	6.8	57,162	14.3%
6	San Andreas SAP	7.0	93,076	23.2%
7	San Andreas SAP	7.2	129,004	32.2%
8	San Andreas SAP	7.4	145,164	36.2%
9	SA SAN+P+S	7.5	152,647	38.1%
10	SA SAN+P+S	7.7	169,198	42.2%
11	SA SAN+P+S	7.8	177,351	44.2%
12	SA SAN+P+S	8.0	193,914	48.4%
13	SA Repeat 1989	7.0	1,855	0.5%
14	Hayward N+S	7.5	49,448	12.3%

Number of customer outages to distribution system (excludes outages due to transmission system)
There are 400,855 customers in San Francisco (1 customer = 1 account)

SF Repair Field Effort Forecast

			Repairs	Repairs	Manhours	Manhours	Manhours
EQ No	Fault / Segment	M	Number of Shaking Repairs	Number of PGD Repairs	Total Field Effort Shake Repairs	Total Field Effort for PGD Repairs	Total Field Repair Effort
1	San Andreas SAP	6.0	2	-	38	-	38
2	San Andreas SAP	6.2	5	-	107	-	107
3	San Andreas SAP	6.4	13	-	269	-	269
4	San Andreas SAP	6.6	26	0	521	31	552
5	San Andreas SAP	6.8	45	2	917	235	1,152
6	San Andreas SAP	7.0	77	7	1,561	663	2,224
7	San Andreas SAP	7.2	116	14	2,347	1,418	3,765
8	San Andreas SAP	7.4	133	23	2,679	2,295	4,974
9	SA SAN+P+S	7.5	139	29	2,814	2,938	5,751
10	SA SAN+P+S	7.7	153	49	3,093	4,967	8,060
11	SA SAN+P+S	7.8	160	63	3,236	6,395	9,631
12	SA SAN+P+S	8.0	175	101	3,535	10,333	13,868
13	SA Repeat 1989	7.0	2	-	32	-	32
14	Hayward N+S	7.5	37	5	739	459	1,198

SF Repair Effort Forecast

EQ No	Fault / Segment	M	Total Field Repair Effort (Manhours)	Logistics Support (Manhours)	Total Effort (Manhours)
1	San Andreas SAP	6.0	38	31	69
2	San Andreas SAP	6.2	107	86	193
3	San Andreas SAP	6.4	269	215	484
4	San Andreas SAP	6.6	552	443	994
5	San Andreas SAP	6.8	1,152	924	2,075
6	San Andreas SAP	7.0	2,224	1,784	4,008
7	San Andreas SAP	7.2	3,765	3,020	6,785
8	San Andreas SAP	7.4	4,974	3,989	8,962
9	SA SAN+P+S	7.5	5,751	4,613	10,364
10	SA SAN+P+S	7.7	8,060	6,464	14,524
11	SA SAN+P+S	7.8	9,631	7,724	17,356
12	SA SAN+P+S	8.0	13,868	11,122	24,989
13	SA Repeat 1989	7.0	32	26	58
14	Hayward N+S	7.5	1,198	961	2,159

Power Outage Durations

			Manhours	Repair Crews	Outage, Days
EQ No	Fault / Segment	M	Systemwide Total Effort	Max People	Repair Time, Days
1	San Andreas SAP	6	69	250	0.03
2	San Andreas SAP	6.2	193	250	0.08
3	San Andreas SAP	6.4	581	250	0.24
4	San Andreas SAP	6.6	1,392	250	0.58
5	San Andreas SAP	6.8	3,528	250	1.24
6	San Andreas SAP	7	8,418	500	2.10
7	San Andreas SAP	7.2	16,962	500	2.81
8	San Andreas SAP	7.4	26,887	1000	3.77
9	SA SAN+P+S	7.5	36,274	1000	4.71
10	SA SAN+P+S	7.7	58,097	1000	6.89
11	SA SAN+P+S	7.8	78,101	1000	8.89
12	SA SAN+P+S	8	124,947	1000	13.57

"Nearly Last Customer Restored"

"average" outage is one-half the listed Outage time, in Days

Transmission + Distribution

EQ No	Fault / Segment	M	Distribution Repair Time, Days	Transmission Repair Time, Days	Best Estimate Power Restoration Time, Days	CDLs	CDSs	Comment
1	San Andreas SAP	6.0	0.03	0.02	0.05	225	0	
2	San Andreas SAP	6.2	0.08	0.05	0.13	1514	0	
3	San Andreas SAP	6.4	0.24	0.10	0.34	7336	0	
4	San Andreas SAP	6.6	0.58	0.15	0.73	22276	0	
5	San Andreas SAP	6.8	1.24	0.25	1.59	73784	0	
6	San Andreas SAP	7	2.10	0.35	2.45	167544	0	
7	San Andreas SAP	7.2	2.81	0.40	3.21	275703	0	
8	San Andreas SAP	7.4	3.77	0.50	4.27	409413	1302779	Load Shed 10 days
9	SA SAN+P+S	7.5	4.71	0.60	5.31	539664	1954168	Load Shed 15 days
10	SA SAN+P+S	7.7	6.89	0.80	7.69	865660	3908336	Load Shed 30 days
11	SA SAN+P+S	7.8	8.89	1.00	9.89	1188293	3908336	Load Shed 30 days
12	SA SAN+P+S	8	13.57	2.00	15.57	2116447	3908336	Load Shed 30 days

1 CDL = Customer Day Lost (=1 customer with no power for 24 hours; or 24 customers with no power for 1 hour)

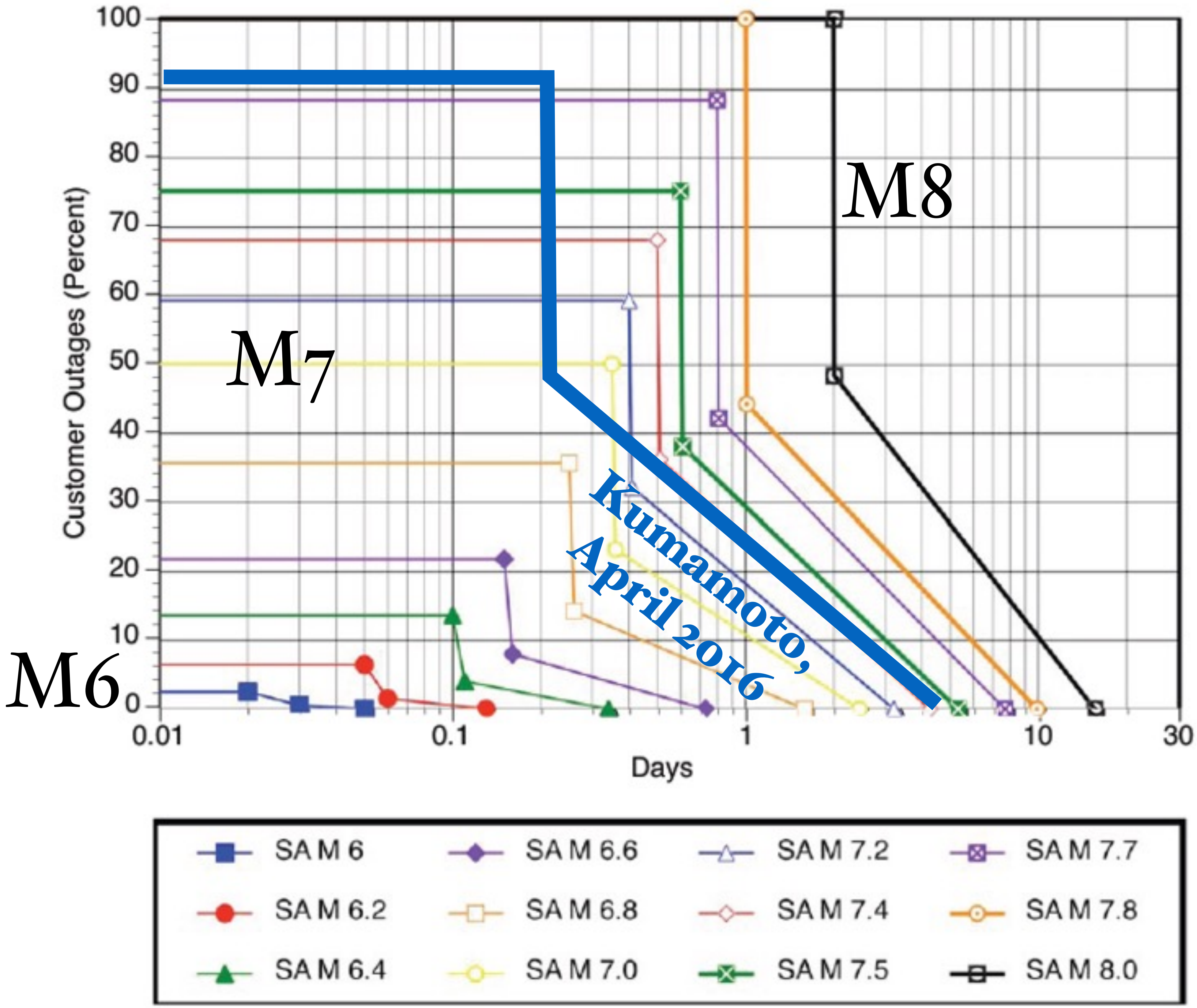
1 CDS = Customer Day with load Shedding. A CDS is where a customer gets power for a portion of the day. CDSs occur when power demand exceeds residual transmission capacity.

Power Outages at “Critical” Water Customers (pump stations)

Pump Station	Feeder	Number of Customers on the Circuit	SA M 6.6 Customer Losing Power (Median)	SA M 7.0 Customer Losing Power (Median)	SA M 8.0 Customer Losing Power (Median)
Allemany	SF H 1106	3780	27%	60%	74%
Bay Bridge	SF Z 1120	2051	2%	10%	70%
Central	SF L 0406	1234	7%	26%	60%
Clarendon	SF H 1102	2249	18%	55%	75%
Crocker Amazon	SF H 0402	1230	9%	31%	52%
Forest Knolls	18th St 0402	1847	3%	12%	30%
Lake Merced	Daly City 1101	539	5%	18%	37%
Lane Street	SF P 1103	3921	22%	51%	65%
Lincoln Park	SF K 1101	5836	14%	50%	78%
McLaren Park	SF H 1106	3780	27%	60%	74%
Summit	SF A 1109	4485	12%	38%	66%
AWSS PS 1	SF Z 1117	1113	1%	4%	69%
AWSS PS 2	SF Y 1127	5673	4%	12%	39%

Outages are due to distribution system damage only.
Excludes outages due to damage to transmission system, load shedding, or forced outages

Power Outages, San Francisco



Power Outage Durations