Seismic Fragility of Power Distribution Systems

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ABSTRACT

This paper examines the seismic performance and fragility of 11 kV to 21 kV low voltage overhead and underground electric distribution systems from the 2014 Napa, California earthquake. There were 127 repairs required for the low voltage power system in this earthquake. It took 38 hours to complete all the repairs. Peak power outages during this time were to 70,000 customers. Fragility models were developed that correlate the observed damage with the level of shaking and ground deformations. Underground performed better than overhead distribution. Design strategies are outlined that should reduce the level of damage in distribution systems in future earthquakes.

INTRODUCTION

Pacific Gas and Electric (PG&E) operates one of largest power generation, transmission and distribution systems in the United States. PG&E serves power to about 7.5 million people in the San Francisco Bay Area, and over 15 million people systemwide. There are many earthquake faults that bisect through PG&E's service area, including the San Andreas fault (capable of magnitude 8 earthquakes), the Cascadia Subduction Zone (capable of magnitude 9 earthquakes), and more than 50 other known Holocene-active faults, most of them capable of M 6.5 to 7.5 earthquakes. On August 24, 2014, one of the smaller faults, called the West Napa fault, ruptured in a Magnitude 6 earthquake. This earthquake impacted the nearby City of Napa, and resulted in power outages that peaked at about 70,000 customers, Figure 1. See (Eidinger et al) for a more complete description of performance of all lifelines in the Napa earthquake.

Over the past two decades, PG&E has upgraded and replaced older equipment and control buildings at high voltage substations (69 kV to 500 kV). These efforts were successful, as there was zero damage that resulted in any outages, to any piece of PG&E high voltage equipment, at six high voltage substations in the Napa area, with each of these substations having experienced PGA > 0.20g. However, there was still damage to low voltage distribution lines (11 kV to 22 kV primaries and low voltage secondaries), and this paper examines the impacts to the distribution system.

Figure 2 shows a map of PG&E's low voltage distribution system in Napa County. Purple lines represent overhead (OH) circuits. Black lines represent underground (UG) circuits. Figure 2 also shows the major urbanized places in Napa County, with more densely urbanized areas indicated by boxed names. The populations in Napa based on the 2013 - 2014 census data is 141,667 people.

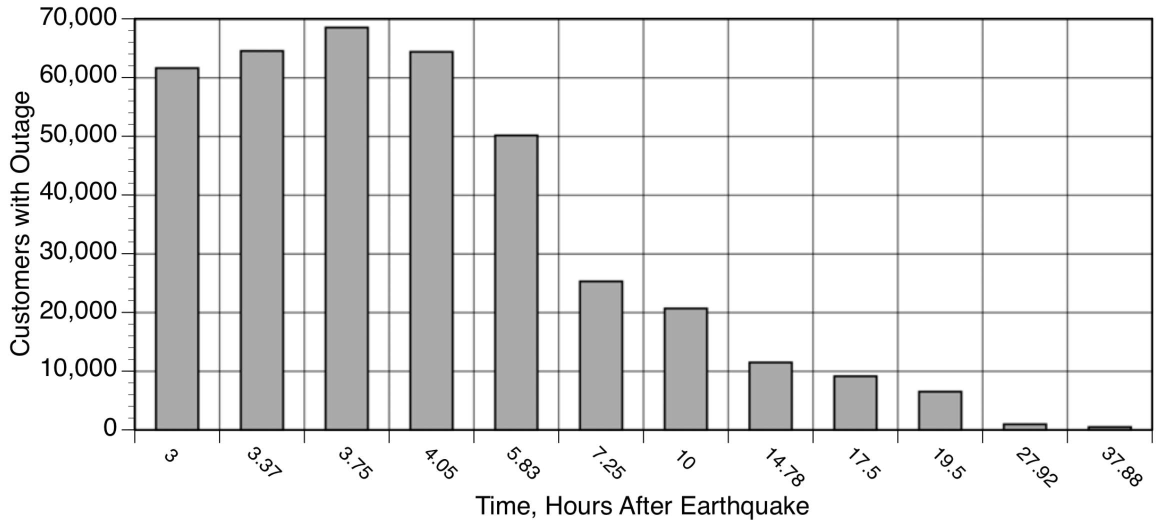

Figure 1. Power Outages

Table 1 lists the lengths of all the low voltage distribution feeders in Napa County. By "length", it is meant the "plan view" length of the feeder. Not included in these lengths are the conductors that take the power from the feeder circuit to transformers (generally a few feet long), and the conductors from the transformers to individual customers (generally at 400 volts or lower).

Item	Length (km)	Percent of Total
All feeders, Napa County	2,398.6	100.0 %
All overhead feeders, Napa County	1,894.5	79.0
All underground feeders, Napa County	504.1	21.0
12 kV Feeders, Napa County	1,855.6	77.4
21 kV Feeders, Napa County	516.3	21.5

Table 1. Lengths of all Feeders, Napa County

In the Napa earthquake, there were essentially no building collapses (there were a few partial collapses). When a building collapses, it can cause damage to the distribution circuit, especially if the low voltage connection to the customer is made overhead. Such damage can be characterized as "pull down" damage. PG&E can do little to prevent damage to the customer's structures.

The age of installation of the low voltage primaries was tabulated for the Napa distribution system. The age of a feeder is used in the seismic evaluations, to reflect that the older the feeder, the more prone it is to age-related effects (stresses in the insulation leading to reduction in dielectric strength, etc.), and thus the additional mechanical stresses imparted by seismic loads could lead to a higher rate of faults in older feeders. Figure 3 shows the installation lengths (by alignment length) by year for Napa.

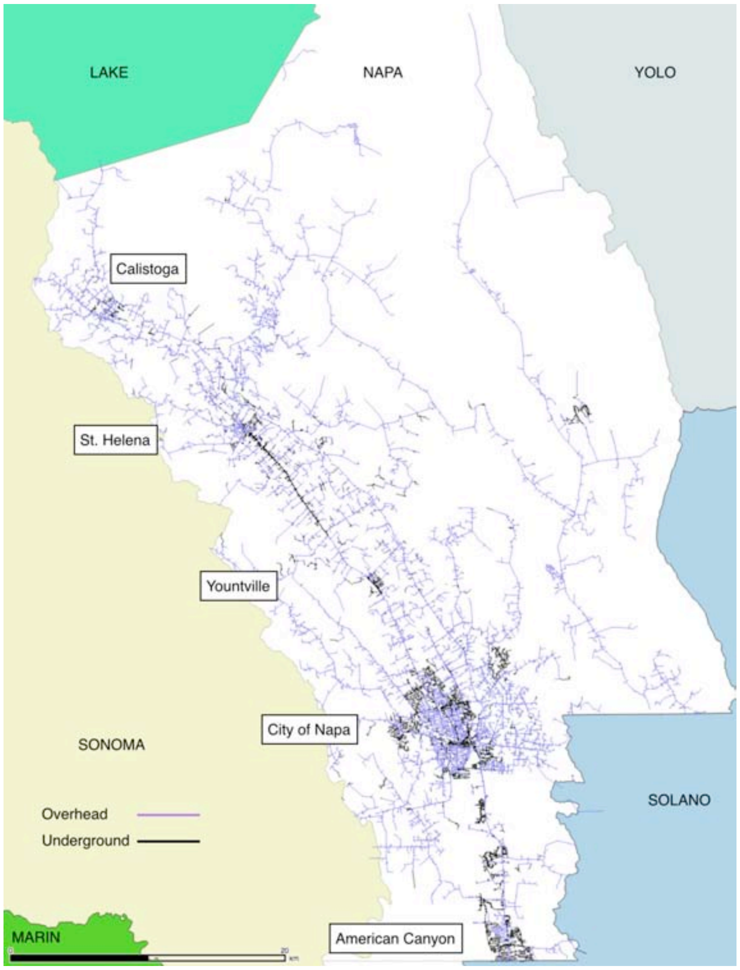

Figure 2. Overhead and Underground Distribution Lines in Napa County

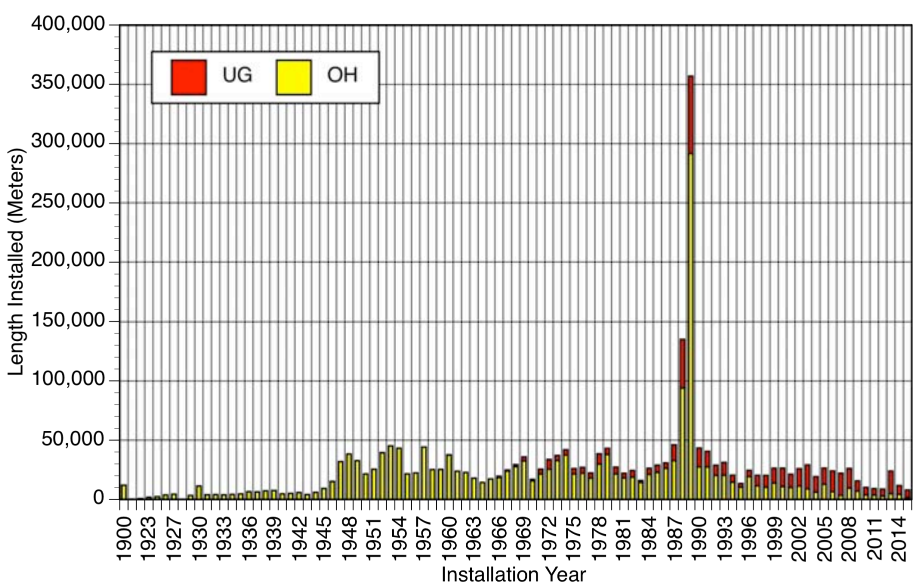

Figure 3. Length Installed by Year (Overhead or Underground) (Napa)

Table 2 provides the statistics for earthquake-related repairs to the distribution system.

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

Table 2. Repair Items and Repair Manhours

SEISMIC SHAKING AND FAULTING IN NAPA EARTHQUAKE

Figure 3 shows the level of shaking in Napa from the August 2014 earthquake. The shaking is shown in terms of Peak Ground Velocity (PGV). The values in this map was computed based on a combination of actual recorded motions (based on 5 instruments in the urban Napa area), a model of the fault rupture, and attenuation models. The motions factor in the local geologic conditions. Yellow stars show locations were there was observed surface faulting, typically about 3 to 9 inches of right lateral offset. There was also some liquefaction and landslides.

DAMAGE TO PG&E's DISTRUTION SYSTEM

We correlated the damage to the distribution system, relative to the levels of exposed hazards. Then, fragility models were developed to match the observed damage with the style of construction used in Napa.

The bulk of the damage to overhead circuits was due to inertial shaking. There were some PGDs due to fault offset (confined to narrow geographic zones) and some PGDs due to liquefaction (confined to narrow zones).

A convenient way to determine the damage is by using a "repair rate per kilometer" measure. This means the chance of a repair per kilometer of length of the circuit.

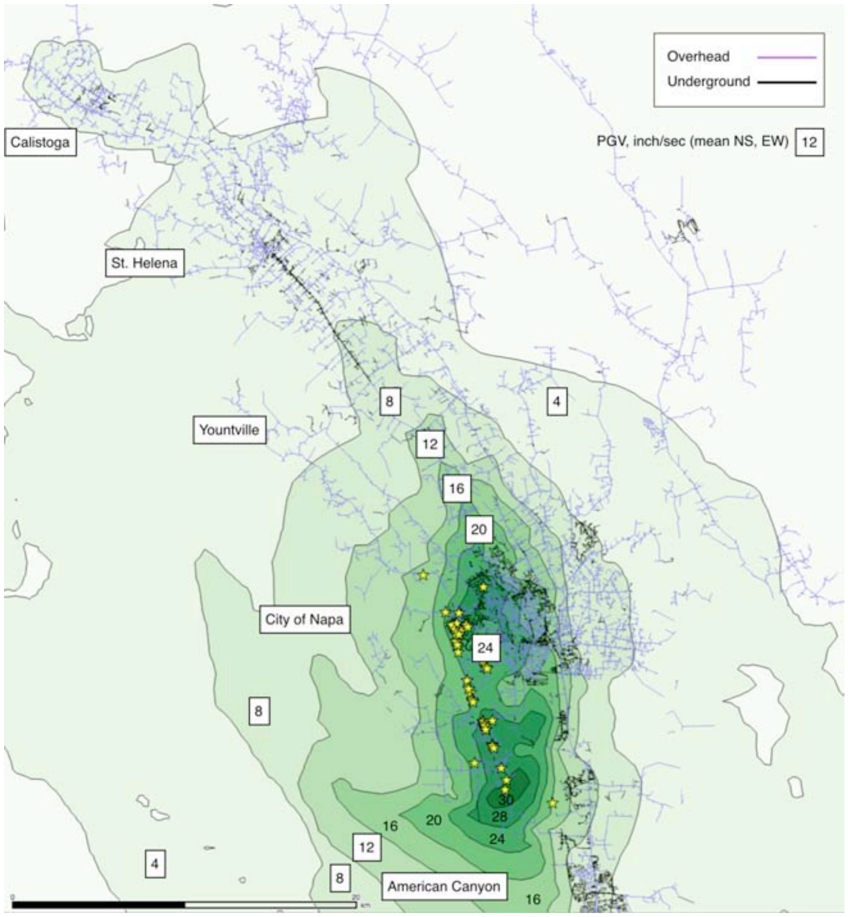

Figure 3. PGV Map, County-wide (full scale 20 km) Mean, inches / second

Figure 4 highlights the location of repairs (black triangles) in the City of Napa with respect to overhead (purple lines) and underground (black lines), along with the PGV levels (green shaded contours) and locations of surface faulting (yellow stars). There is a strong correlation of overhead repairs with higher PGV; and very little (if any) correlation of damage of overhead or buried circuits with surface faulting location. There was no damage to buried feeders due to surface faulting that was on the order of 3 to 9 inches of right lateral offset, indicated by the yellow stars in Figure 4; this strongly indicates that PG&E's design practice to place buried feeders in PVC (or similar) ducts, leaves enough slack in between the conductor cable and the PVC duct to accommodate a few inches of fault offset, or, for that matter, a few inches of PGD due to liquefaction or landslide.

FRAGILITY OF PG&E's DISTRUTION SYSTEM

We compared the 2,398.6 km of PG&E's distribution lines in Napa County with the level of shaking they were exposed to. We did this as follows:

- Overlay the PG&E distribution system lines (~2,400 km) over five different maps. These maps are for PGA, PGV, PSA03, PSA10, PSA30 (peak ground acceleration, peak ground velocity, peak spectral acceleration at 0.3 seconds, peak spectral acceleration at 1.0 seconds, peak spectral acceleration at 3.0 seconds, all mean horizontal).

- We computed the level of shaking at each distribution segment (average about 100 meters long) to assign to each segment the five seismic hazard bin levels.

- We aggregated the length of feeder circuit in each hazard value bin.

The results using PGA, PGV and SA(T=3.0 seconds) and PGV are presented in Figures 5 and 6. Some observations from Figures 5 and 6:

- There is a clear trend of increasing repairs with increasing seismic hazards. The R^2 values for PGA (0.24) is much lower than for SA(T=3) (0.96). This suggests that PGA is not a good a predictor. The R^2 value for SA (3.0 seconds) (0.96) is very high. Mostly, we think that the better correlation for long period motion is because the poles and wire systems are long period structures.

- Since the mid-1950s, after observing hundreds of transformer failures in the 1952 Taft earthquake, PG&E has directly bolted overhead transformers to wood poles (and never to the cross arms). No overhead transformers "fell to the ground" in this earthquake, even if they were supporting heavy transformers. No overhead poles "fell over" due to shaking. This helps confirm that wind-related design of wood poles is generally sufficient for strong ground shaking.

- The primary reason(s) for the observed damage is insufficient slack between adjacent overhead items, leading to "snap loads" when available slack is overcome; and wire slapping leading to entanglements and burnt wires. The typical failures were to broken cross arms (with related hardware), broken attachments from overhead secondaries to adjacent structures, and conductor burns. In a few locations along the Napa river exposed to liquefaction, poles did tilt 5° to 10°, but none fell over.

- At the highest levels of PGA (0.6g or higher), there appears to be a decreasing rate of damage. This seems "counter-intuitive", but in fact, if we assume that long period motions drive motion of the conductors, and hence loads due to insufficient slack issues, or wire-slapping issues, this trend might not be unexpected.

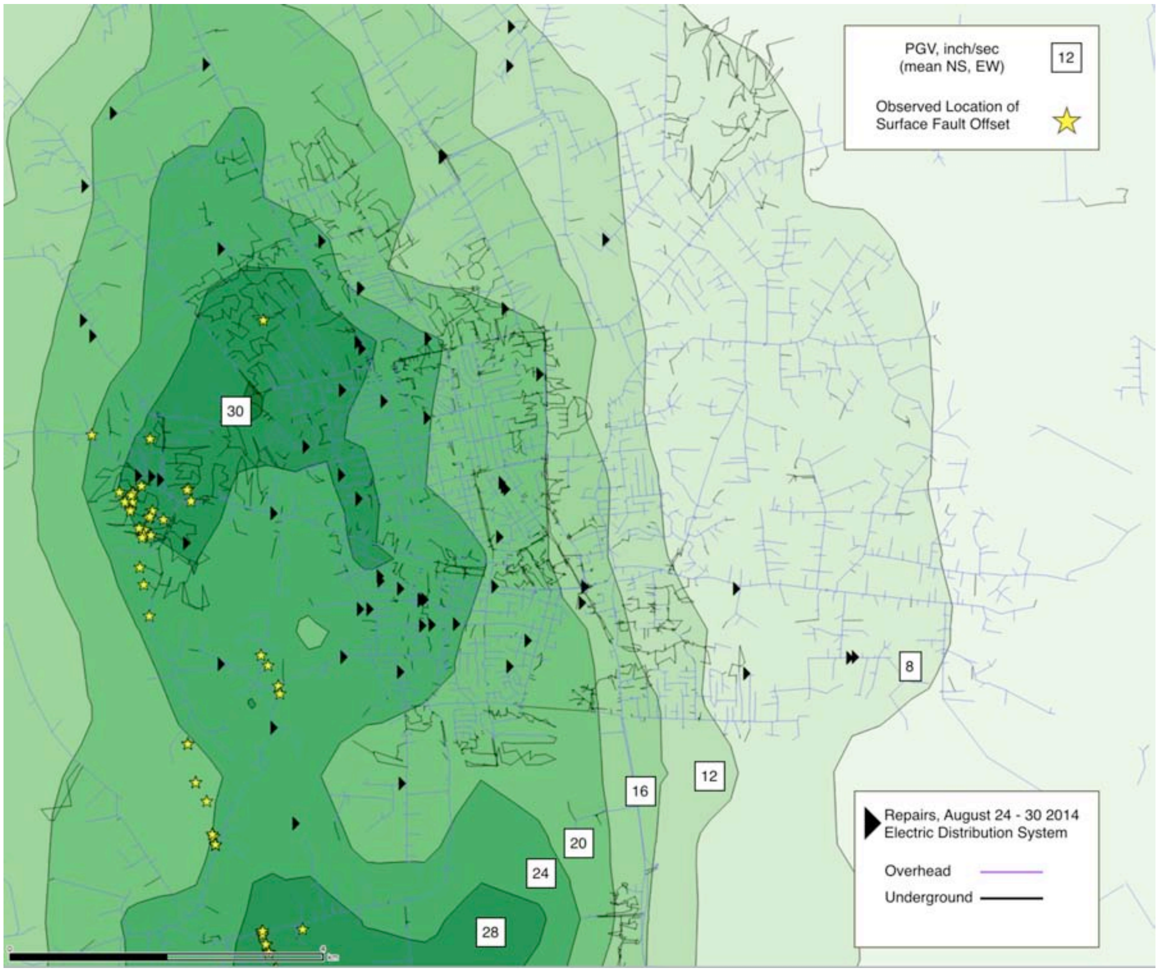

Figure 4. Repairs, City of Napa

Based on these findings, we think that use of PGA (or short period spectral accelerations) for predicting damage to overhead distribution systems is inferior. Use of the SA (T = 3 seconds) value appears to be best, and reflects the likely range of periods of combined pole and wire systems. If forecasting overhead damage in a "near real time" situation, if the long period information (T = 3 Spectra value) is not yet available, then use of PGV can be used with reasonably good results.

Table 3 provides the recommended fragility models for overhead and underground distribution components for inertial shaking.

Style of distribution circuit	k1	k2	k3
1. Overhead primaries with overhead secondaries	1.0	1.0	0.8 to 1.25
2. Overhead primaries with underground secondaries	1.0	0.75	0.8 to 1.25
3. Underground in non-filled duct	0.3	1.0	1.0
4. Underground in filled duct	1.0	1.0	1.0

Table 3. Repair Rate, due to Shaking

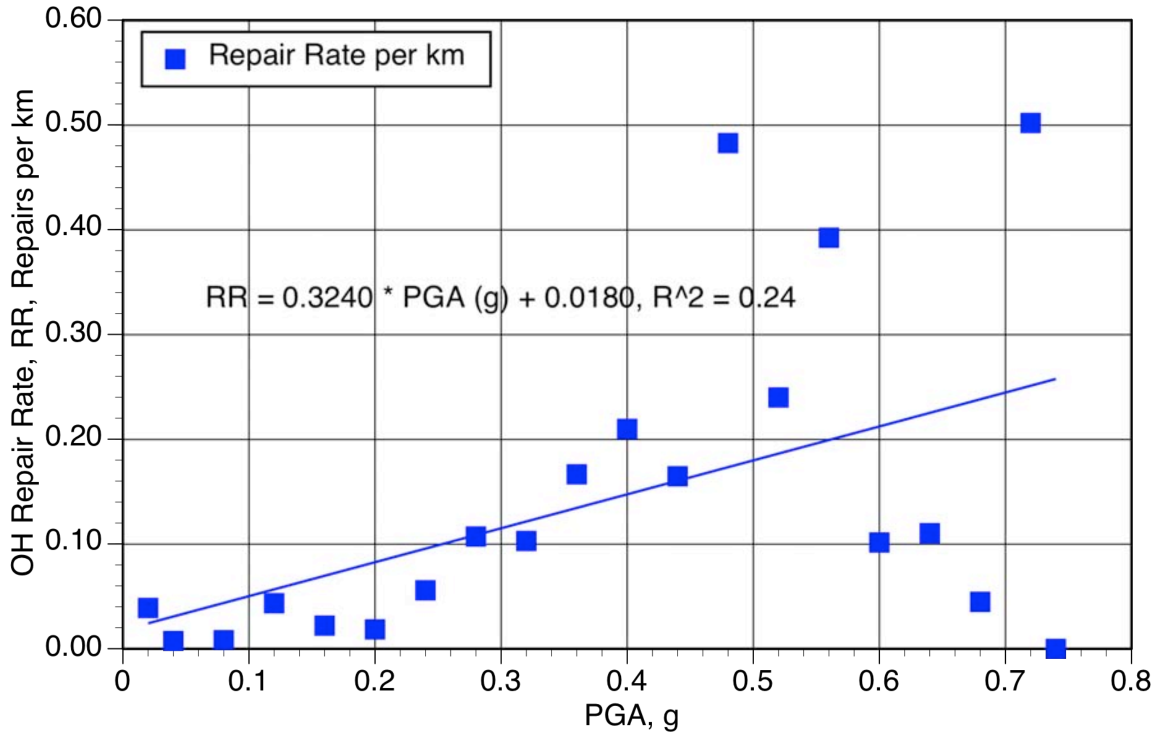

Figure 5. Repair Rate, Overheads, Using PGA

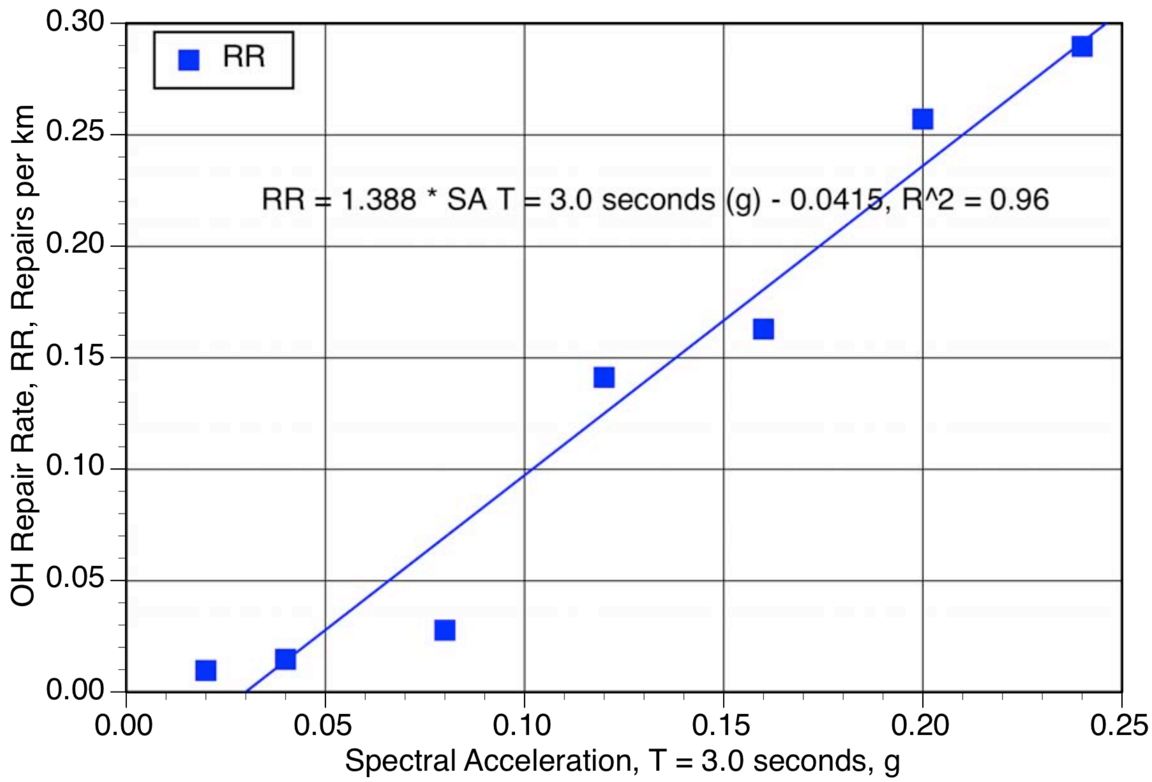

Figure 6. Repair Rate, Overheads, Using SA (T = 3.0 seconds)

k1 = 1.0 for overhead construction, 0.3 for typical underground construction. Typical underground construction used by PG&E are cables within an empty (unfilled) conduit (duct), with all conduits encased in unreinforced concrete. Filled ducts are sometimes used where the ducts have less than about 2 feet of cover. In these cases, there is no cable slack available to accommodate ground shaking.

k2 = 1.0 for overhead secondaries, 0.75 for underground 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 a reasonable proxy for the age-related effects on wood pole and cross arm strength owing the cumulative effects of termites and wood rot.

Overhead (Cases 1, 2). If SA(3.0 second) is available:

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

or, if SA(30) is not available:

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

Underground (Cases 3, 4). The damage rate is assumed to be proportional to strain induced into the duct. Prior work for buried pipes shows that the repair rate is directly proportional to ground strain, which in turn is proportional to PGV.

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

where RR(shake) is repairs per km, and k1, k2, k3 are from Table 3.

LIQUEFACTION AND LANDSLIDE FRAGILITY MODEL

The damage rates for feeders due to liquefaction and landslide are described in Table 4.

Four types of feeders are considered: Overhead primaries with overhead secondaries (Case 1); Overhead primaries with underground secondaries (Case 2); Underground primaries with underground secondaries, in unfilled conduits within unreinforced concrete ducts (Case 3); Underground primaries with underground secondaries, in filled conduits within reinforced concrete ducts (Case 4).

The repair rate model is:

$$RR_{liq} = k1 * k2 * k3 * PGD^{1.1245}, \; PGD > 0.5 \; inches$$
$$RR_{liq} = 0, \; PGD < 0.5 \; inches$$

where RR(liq) is repairs per 1,000 feet, and PGD is in inches; 0.0 if PGD ≤ 0.5 inches.

Case	k1	k2	k3
1. Overhead primaries and secondaries	0.00125	1.0	0.8 to 1.25
2. Overhead primaries, underground secondaries	0.0025	1.0	0.8 to 1.25
3. Underground in non-filled duct	0.01	1.0 (no reinforcement) 0.125 (with reinforcement)	0.8 to 1.25
4. Underground in filled duct	0.026	1.0 PILC 0.80 XLPE or EPR	0.8 to 1.25

Table 4. Repair Rate, due to Liquefaction and Landslide PGDs

For cases where there is steel reinforcement in the underground concrete ducts, this substantially improves the performance of Case 3 buried feeders.

k1 reflects the style of construction. k2 reflects the type of duct bank (for unfilled conduits) or the type of conductor (for filled conduits). Case 3. k2 is 1.0 for underground cables in unfilled conduits in unreinforced concrete duct banks; or 0.125 if in unfilled conduits in reinforced concrete duct banks. k3 = 1.25 if year of construction is 1945 or earlier; 1.0 if 1946 to 1990; 0.80 for 1991 or later. The k3 (age) factor is meant to reflect the cumulative effects of historical loading on underground cables, whereby a cable with longer in-service conditions is more likely to have had multiple high load (high amp, high temperature) conditions, which tends to degrade the insulation and lead to a higher repair rate. 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.

REPAIR TIMES

Given the range of damage, one of PG&E's primary post-earthquake activities will be to repair the damage in order to restore power to customers, in a safe manner. The logistics to make the repairs is basically as follows:

- Identify from customer feedback or PG&E crew direct observation where the outages are located. For minor events, customer-feedback (via (1-800) number call-in methods) might be sufficient. For major events (like earthquakes), phone systems might be saturated or otherwise damaged, and relying only on customer-call-ins is not likely to provide a clear picture of damage. Locating the damage for overheads can usually be done by visual observation. Locating the damage for undergrounds can be done using specialized test equipment that can indicate the distance form the test location where a cable is faulted. Send a "trouble team" to determine the style of damage, and the type of repair effort needed to make the repair. Send an electric distribution crew to make the repair. Provide coordination for all these activities.

There can be a variety of issues that compound the repair effort in the distribution system. For example:

- If the source of power, at the high voltage substation, has no power, then none of the feeders from the substation will have power. If a distribution circuit has no power, then other than gross visual failures (like falling of a wood pole, which is very rare, but possible), it will be difficult to discern the extent of damage in the distribution system. If there are ongoing fires, it might not be safe for PG&E crews to work in an area until the fires are controlled or put out. After a moderate to large earthquake, PG&E or government officials might require that an area be de-energized until such time that all areas are checked for possible leaking gas. In these areas, it might not be possible for PG&E electric crews to work. In some areas there may be coincident damage to roads and bridges that cause very lengthy traffic jams or outright lack of access by vehicles. In some areas there may be coincident damage to structures that result in debris into roadways. Or, the structures may still be standing but seriously damaged, and access near the affected structures are precluded due to threat of aftershocks causing further damage and collapse.

In the Napa 2014 earthquake, essentially none of these compounding factors occurred. PG&E power was available at all times at all transmission substations. Road closures occurred, but there were always work-arounds. Some structures did collapse, but the ensuing damage and cordoned-off zones near dangerous buildings did not materially hamper PG&E electric crew access.

With these issues in mind, Table 2 shows the total repair effort was 4,478 manhours, or an average of 35 manhours per repairs. While the "average" is 35 hours, about half of the total effort is assigned to the category "Logistics", which is the labor effort to provide in-office coordination.

For larger earthquakes, the damage due to PGD-related issues becomes more important, and eventually dominates the repair effort. Repair of a buried distribution cable is assumed to require about 102 manhours in the field.

The time needed to complete all the repairs will depend upon how many crews are mobilized. In the Napa 2014 earthquake, all repairs were complete in about 38 hours, suggesting that the effort required about 236 people. PG&E is a large company, with about 20,000 total employees. In the Napa 2014 earthquake, some crews came to Napa from other nearby counties.

DESIGN CONSIDERATIONS

For low voltage distribution systems, design recommendations to reduce future damage in areas not prone to liquefaction or landslide include: adding wind spacers to overhead primary wires; adding slack to secondary wires; using high toughness composite insulators; automatic switching of circuit breakers at substations upon sensing high S-wave motions; using underground secondaries; using underground primaries. In areas prone to liquefaction or landslide, the use of direct-burial cables should always be avoided, and the use of conduits with empty annular spaces can provide good protection for modest levels of PGDs (up to about 6-inches / 15 cm); placement of conduits within concrete duct banks is useful for mechanical protection, and placement of reinforcement within the concrete duct banks can provide some measure of protection in liquefaction and landslide and fault offset zones.

ABBREVIATIONS AND UNITS

kV = kiloVolt. OH = overhead. PGA = Peak Ground Acceleration, expressed in g (1 g = 32.2 feet / sec / sec = 981 gal. PGD = permanent ground deformation. PGV = Peak Ground Velocity. 1 inch / sec = 2.54 cm / sec. UG = underground. 1 mile = 1.60934 kilometers (km). 1 foot = 0.3048 meters. T = period (seconds).

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REFERENCES

Eidinger, J (editor), Kwasinski, A., Yashinsky, M., Andrew J., Schiff, A. Tank, A., South Napa M 6.0 Earthquake of August 24 2014. Rev. 2. http://www.geEngineeringSystems.com, March 12 2016.