16th World Conference on Earthquake Engineering, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 0167 (Abstract ID)

Registration Code: S-A1464482589

FRAGILITY OF ELECTRIC POWER DISTRIBUTION SYSTEMS

J. Eidinger[(1)]

[(1)] *President, G&E Engineering Systems Inc., Eidinger@geEngineeringSystems.com*

Abstract

A vital aspect on the restoration of civilization to good working order after earthquakes is the restoration of the power grid. For the past 46 years, ever since the damage at the Sylmar converter station in the 1971 San Fernando earthquake, the focus has been on the damage of high voltage equipment at substations, with very little attention to the damage of low voltage distribution systems. In California, there are now more than 4 million low voltage distribution power poles, and hundreds of thousands of kilometers of low voltage circuits. What is needed are rational methods to analyze this huge inventory, in a way that can develop accurate power outage forecasts, and ideally provide insight as to what actions can be done now to reduce the potential for power outages in future earthquakes.

This paper presents a detailed examination of the performance for Pacific Gas and Electric's (PG&E) low voltage distribution system in the 2014 Napa earthquake. In that earthquake, there was no material damage to the high voltage transmission system, but damage to the distribution system resulted in power outages to 70,000 PG&E customers. The last customer had power restored in about 38 hours.

This paper examines the damage that caused these outages, what level of effort was needed to make repairs, and describes new fragility models that can accurately forecast this damage.

Keywords: Electric; Distribution; Fragility; Napa; PG&E

1. 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 and caused a moment Magnitude 6 earthquake. This earthquake impacted the nearby City of Napa, and resulted in power outages that peaked at about 70,000 customers, Fig.1. One "customer" corresponds to one billing account. See [1] 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 most of the older equipment and control buildings at six high voltage substations (69 kV to 230 kV) located within 30 km of the August 24 2014 epicenter. These efforts were successful, as there was zero damage that resulted in any outages, to any piece of PG&E high voltage equipment at the six high voltage substations in the Napa area, even though each of these substations having experienced PGA between 0.20g and 0.30g (and possibly somewhat higher). All the 70,000 customer outages was due to damage of low voltage distribution lines (11 kV to 22 kV primaries and low voltage secondaries).

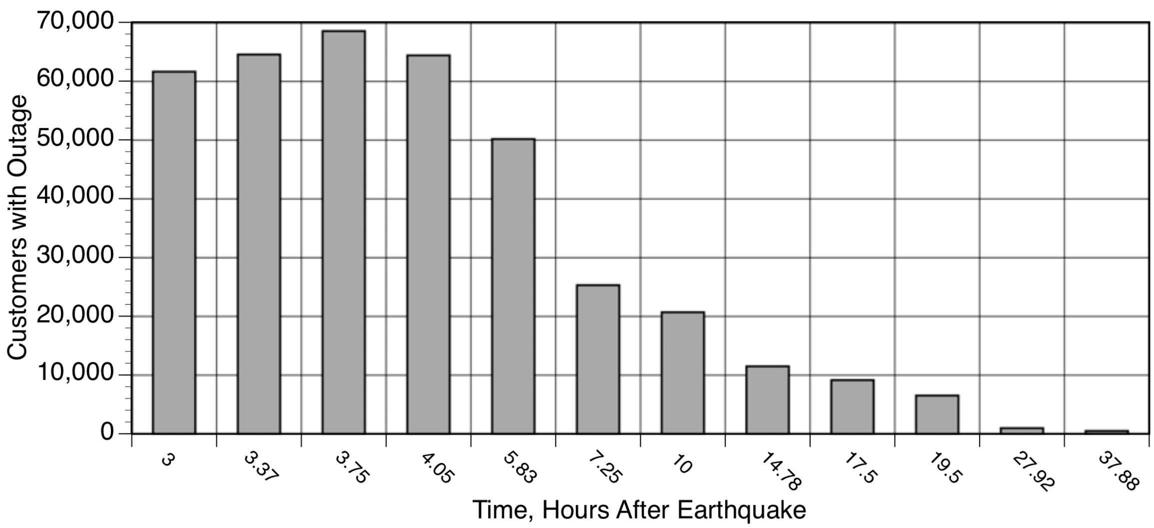

Fig. 1 - Power Outages

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 primary feeder circuit to transformers, and the secondary conductors from the transformers to individual customers.

Table 1. Lengths of all Feeders, Napa County

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

Fig. 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. Fig. 2 also shows the major urbanized places in Napa County, with more densely urbanized areas indicated by boxed names. The population in Napa based on the 2013 - 2014 census data was 141,667 people.

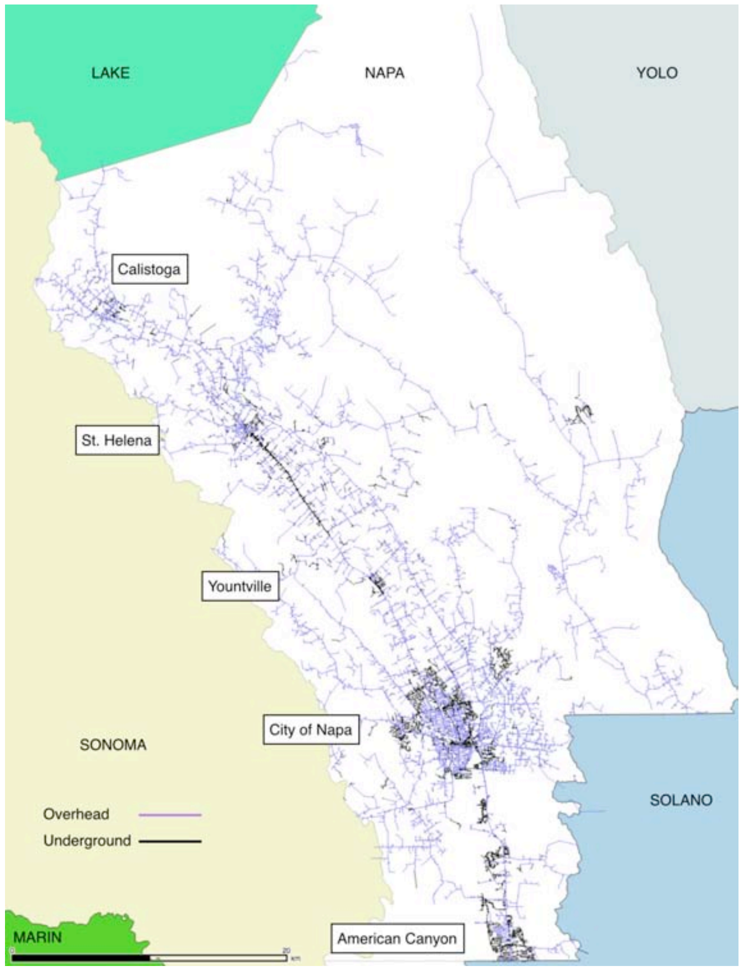

Fig. 2 - Overhead and Underground Distribution Lines in Napa County

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 mechanical stresses imparted by seismic loads could lead to a higher rate of faults in older feeders. Fig. 3 shows the installation lengths by year for Napa, and shows that underground feeders have been the most common style of installation over the past 25 years. There still remains a large inventory of overhead feeders, the oldest of which is now over 100 years old.

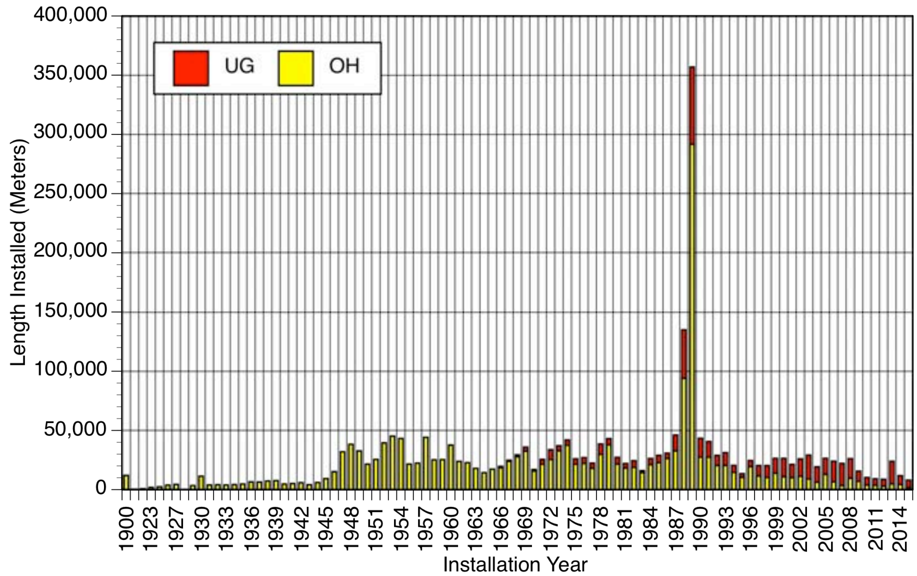

Fig. 3 - Length Installed by Year (Overhead or Underground) (Napa)

After the earthquake, a compilation of actual repairs to the distribution system was made, and Table 2 provides the statistics for earthquake-related repairs. The column "Number of Repair Items" reflects the number of different locations where similar types of damage had to be repaired. The column "Total Manhours" reflects the cumulative time (in man-hours) needed by PG&E repair crews to complete all those repairs. The column "Average Manhours per Repair Item" reflects the average effort to make each type of repair.

Table 2 - Repair Items and Repair Manhours

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 wire hardware	45	6	8
Hardware / Framing	34	3	11
Insulator	42	3	14
Jumper	81.5	8	10
Switch / Junction 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 shows that repairs to overhead items (conductors, connectors, cross arms, etc.) often take between 10 to 20 manhours per item, while repairs to underground items take between 36 and 79 manhours (3 to 4 times longer). Another key item is that nearly half the total effort (2,000 manhours) was required for "office" staff to provide logistical support for the repair crews in the field.

2. Seismic Shaking and Faulting in Napa Earthquake

Fig. 4 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 were computed based on a combination of actual recorded motions (based on 5 strong motion instruments in the urban Napa area), a model of the fault rupture, and ground motion attenuation models. These motions factor in the local geologic conditions. Yellow stars show locations were there was observed surface faulting, ranging from about 7 to 22 cm of right lateral offset.

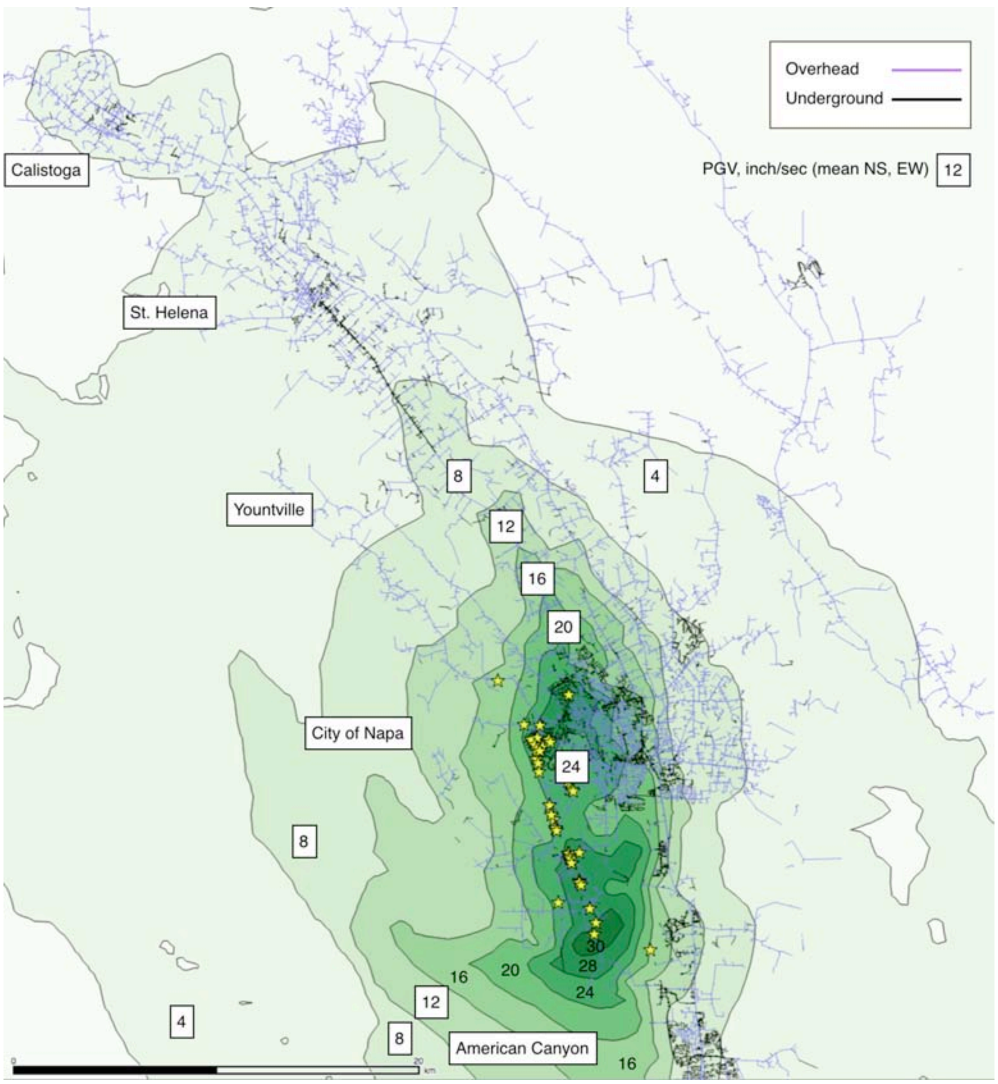

Fig. 4 - PGV Map, County-wide (full scale 20 km). PGV in inches / second

3. Damage to PG&E's Distribution 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 permanent ground deformations (PGDs) due to fault offset (confined to a narrow geographic zones) and some PGDs due to liquefaction (also confined to few city blocks).

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.

Fig. 5 highlights the location of repairs (black triangles) in and near 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 observed 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 occurred at the locations indicated by the yellow stars in Fig. 5; 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 about 10 to 20 cm of PGD.

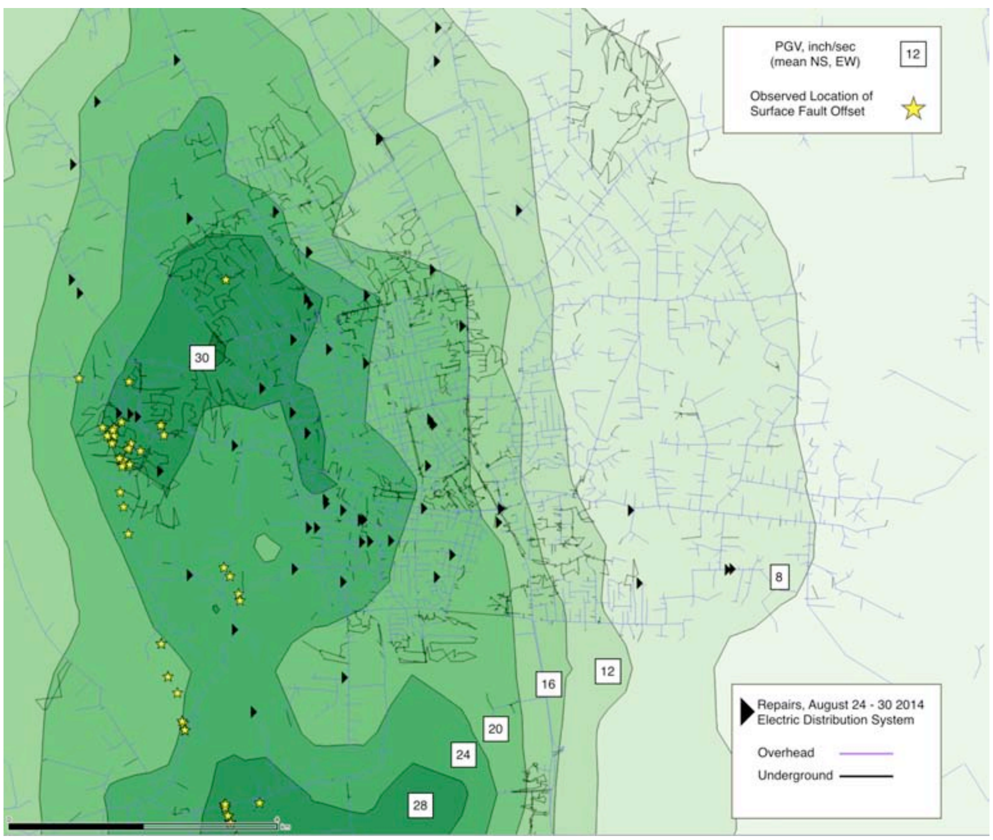

Fig. 5 - Electric Distribution System Repairs near the City of Napa

4. Damage Statistics for PG&E's Distribution 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 by overlaying the PG&E distribution system lines over maps with five different measures of seismic hazard. These maps were computed for PGA (peak ground acceleration), PGV (peak ground velocity), and PSA (peak spectral acceleration at 0.3 seconds, 1.0 seconds, and 3.0 seconds, 5% damping). We then computed the level of shaking at each distribution segment (about 20,000 individual segments, the common segment being about 100 meters long) to assign to each segment each of the five seismic hazards. We then aggregated the known repairs and the length of feeder circuit in each hazard value bin.

The results using PGA and PSA(T=3.0 seconds) are presented in Figs. 6 and 7. These figures show that there is a clear trend of increasing repairs with increasing seismic hazard. The regression R^2 value for PGA (0.24) is much lower than for PSA (T=3 seconds) (0.96). This suggests that PGA is not a very good a predictor. The R^2 value for PSA (T = 3 seconds) is very high. Mostly, we think that the better goodness-of-fit for long period motion is because the overhead poles and wire systems are mostly long period structures and the level of damage is largely due to the differential movements between overhead poles that lead to high cable "snapping" forces if the available slack is insufficient to accommodate the relative movements between poles or between poles and the customer's buildings.

Since the mid-1950s, after observing hundreds of transformer failures in the 1952 Taft earthquake, PG&E has directly bolted overhead transformers and regulators to wood poles (and never to the cross arms). Not surprisingly, no overhead transformers "fell to the ground" in the 2014 Napa earthquake, even if the poles were supporting heavy transformers. No overhead poles "fell over" due to shaking. This helps confirm that PG&E's wind-related design of wood poles coupled with suitable installation practices of pole-mounted transformers is generally sufficient to accommodate the inertial stresses imposed due to 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 2° to 10°, but no poles fell over, and these tilts were not sufficiently severe as to cause faults or warrant immediate replacement.

At the highest levels of PGA (0.6g or higher), Fig. 6 shows that there is a very large increase in scatter in the damage data; either there was very little damage or very large damage. This seems "counter-intuitive", but in fact, if one assumes that long period motions drive motion of the conductors, and hence loads due to insufficient slack issues, as well as wire-slapping issues, this trend might not be unexpected as there is not much correlation of PGA with longer period pulse-type earthquake motions.

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 PSA (T = 3 seconds, 5% damping) value appears to be best, and reflects the likely range of periods of combined pole and wire systems. If one needs to forecast overhead damage in a "near real time" situation, (like within a few minutes post-earthquake, as soon as instrument recordings can be processed), if the long period information (T = 3 Spectra value) is not yet available, then use of PGV with equations (3) and (4) can be used with reasonably good results.

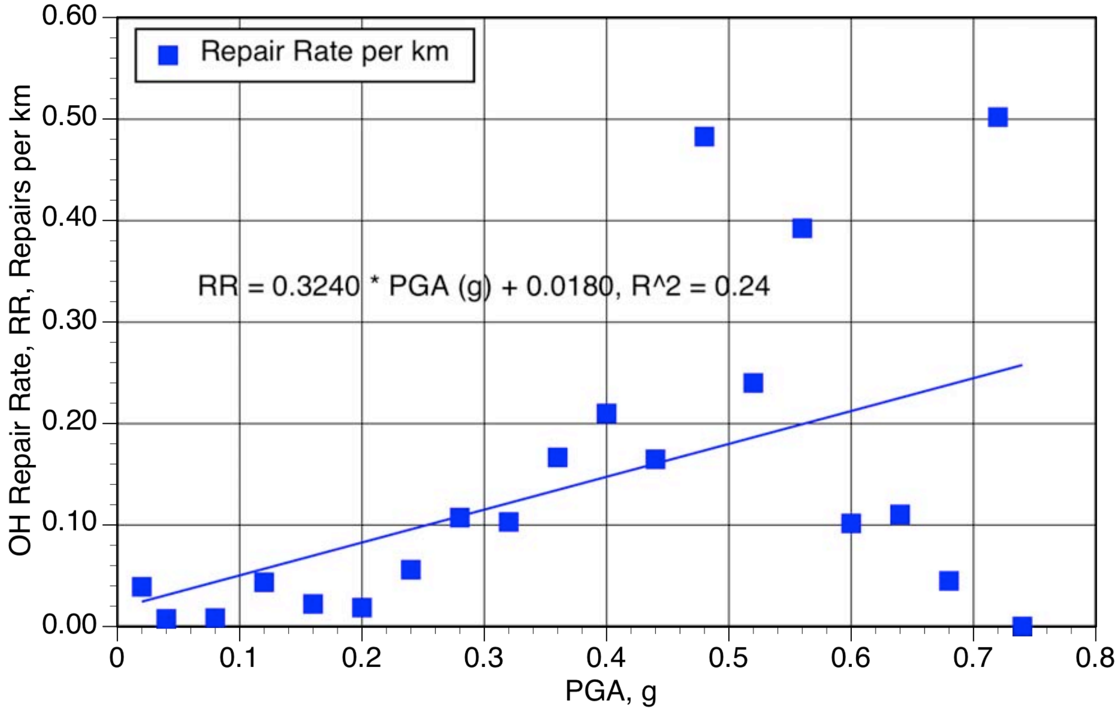

Fig. 6 - Repair Rate, Overheads, Using PGA

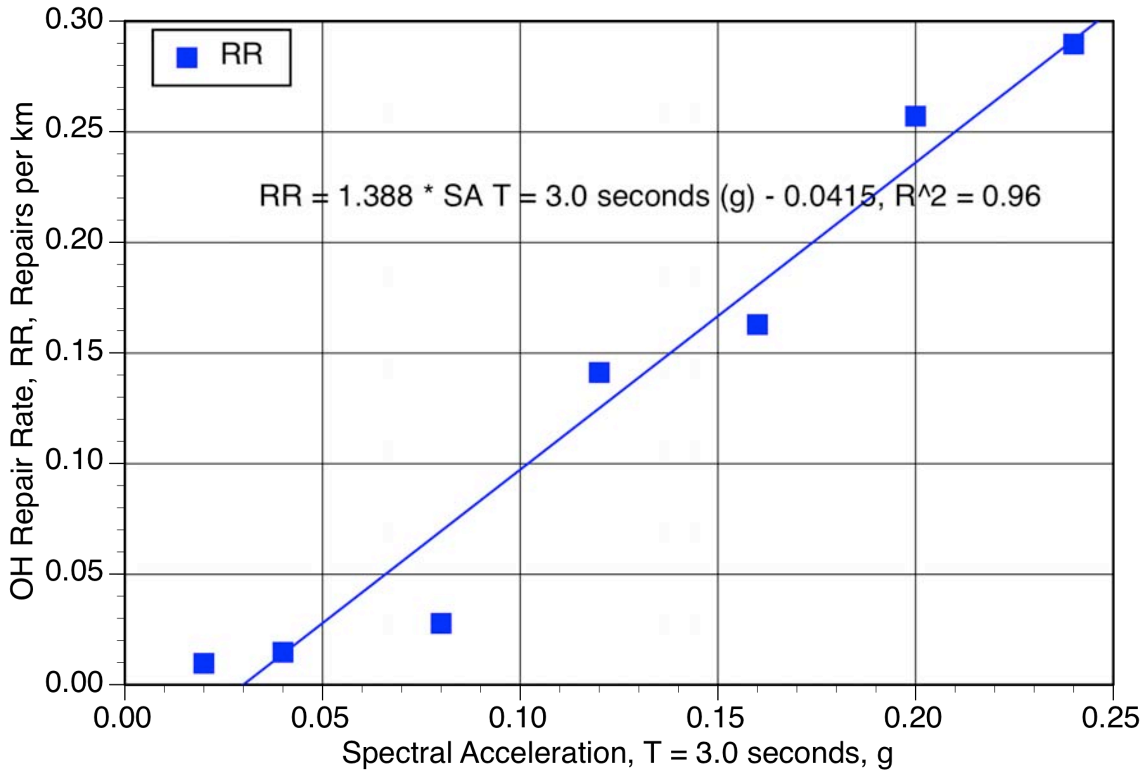

Fig. 7 - Repair Rate, Overheads, Using PSA (T = 3.0 seconds)

5. Ground Shaking Fragility Model

We processed the damage data for PG&E's system in Napa to develop fragility models for overhead distribution systems. For underground systems, this paper factors in the performance of PG&E's underground cables (generally constructed in ducts) as well as Orion's [2] underground cables (generally in direct burial).

Table 3 and the following formulae provide the recommended fragility models for overhead and underground distribution components for inertial shaking.

Table 3. Repair Rate Constants, due to Shaking (for Equations 1, 2, 3, 4, 5)

Case, 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	0.984	1.0	1.0
4. Underground in filled duct	3.28	1.0	1.0

k1 = 1.0 for overhead construction (Cases 1, 2), 0.3 for typical underground construction (Case 3). 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 0.6 meters of cover (Case 4), and in these cases, there is no cable slack available to accommodate ground shaking, leading to an increased level of strain in the conductors.

k2 = 1.0 for overhead secondaries, 0.75 for underground secondaries (Case 2). The 0.75 value reflects that damage to overhead secondaries was about 25% of all the damage, and thus k2 = 0.75 reflects for situations where there are no 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 a reasonable proxy for the age-related effects on wood pole and cross arm strength owing the cumulative effects of termites and wood rot.

Cases 1, 2. (Overheads).

If $PSA_{(3.0 \text{ second})}$ is available, use Eqs. (1) or (2):

$$RR_{shake} = k1 * k2 * k3 * \left(1.388 * PSA_{T=3.0} - 0.0415\right),\ PSA_{T=3.0} \geq 0.03g \qquad (1)$$

$$RR_{shake} = 0.0,\ PSA_{T=3.0<0.03g} \qquad (2)$$

or, if PSA_{30} is not available, use Eqs. (3) or (4):

$$RR_{shake} = k1 * k2 * k3 * \left(0.0111 * PGV - 0.0366\right),\ PGV \geq 3.3\ \ inch/\sec \qquad (3)$$

$$RR_{shake} = 0.0,\ PGV < 3.3\ \ inch/\sec \qquad (4)$$

Cases 3, 4 (Underground). The damage rate is assumed to be proportional to strain induced into the duct. Prior work for buried pipes [3] shows that the repair rate of buried pipes (and cables) is directly proportional to ground strain, which in turn is proportional to PGV. Use Eq. (5).

$$RR_{shake} = k1 * k2 * k3 * 0.00187 * PGV,\ inch/\sec \qquad (5)$$

where RR_{shake} is repairs per km, and k1, k2, k3 are from Table 3. Comparing common overhead installations (Case 1) with common underground installations (Case 3) for PGV = 25 inches/second, overheads are about 5 times more likely to be damaged than undergrounds.

6. PGD Fragility Model

The damage rates for feeders due to PGDs from 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 Eqs. (6) or (7):

$$RR_{liq} = k1 * k2 * k3 * PGD^{1.1245}, \ \ PGD > 0.5 \ \ inches \tag{6}$$

$$RR_{liq} = 0, \ \ PGD < 0.5 \ \ inches \tag{7}$$

where RR_{liq} is repairs per 1,000 feet, and PGD is in inches; 0.0 if PGD ≤ 0.5 inches.

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

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

k1 reflects the style of construction. The 0.01 value for Case 3 reflects the damage rates observed in Napa for PG&E's buried cables that were exposed to a few inches of PGD movements, yet had no observed damage. The 0.026 value for underground cables in filled ducts reflects the observed high failure rates for Orion's buried cables (direct burial) in the Christchurch 2010 and 2011 earthquakes where PGDs reach a meter or more. The k1 values for overhead poles reflects that with sufficiently large PGDs, overhead poles will tilt (caused by loss of bearing strength), and with sufficient tilt, they will eventually fail. PGDs of about a meter rarely fail overheads, but PGDs of several meters (say due to a deep-seated landslide) will often fail overheads.

For Case 3 buried feeders, 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. For case 4 buried feeders, the k2 variable reflects the style of conductor, with PILC conductors having more sensitivity to incremental mechanical stresses owing to perceived weaker joinery than newer XLPE (cross-linked polyethylene) or EPR (ethylene propylene rubber) insulated cables; between PG&E and Orion, we observed a lower failure rate, given equal hazards, for XLPE and EPR styles of cables than older PILC style of cables.

Example. There were about 20 km of buried feeders exposed to some form of PGD (either some liquefaction, landslide or fault offset), with about 6 repairs total, or a repair rate of about 6 / (20 * 3.28) = 0.0915 repairs per 1,000 feet, which is the sum effect of both inertial shaking and PGD loading. Equation (6) forecasts a rate of 0.075 repairs per 1,000 feet due to PGD, and Equation (3) forecasts 0.014 repairs per 1,000 feet, or a total of 0.089 repairs per 1,000 feet, which is very close to the actual observations.

7. Repair Times

Given the range of damage, one of PG&E's primary post-earthquake activities was 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 damage and outages are located. For minor events, customer-feedback (via "1-800" phone 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 from the test location where a cable is faulted. The power company sends a "trouble team" to determine the style of damage, and the type of repair effort needed to make the repair. Then, an electric distribution crew is sent out to make the repair. Back-office efforts by the power company are also needed to provide the necessary coordination for all these activities.

There can be a variety of issues that compound the repair effort in the distribution system. The following provides several such examples:

For the common cases, and excluding distributed generation), then if 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, or major movement of a cross arm, or pullout of a conductor from a customer's secondary line drop), it might be difficult to discern the extent of damage in the distribution system. If there are ongoing fires, it might not be safe for crews to work in an area until the fires are controlled, extinguished, and the area determined by the fire department as sufficiently safe as to allow access by the power company (example: Oakland Hills fire 1991). After a moderate to large earthquake, the power company or government officials might require that an area be de-energized until such time that all areas are checked for possible leaking gas (example: San Francisco Loma Prieta Earthquake 1989). 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 (example: Christchurch Earthquakes in 2011). 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. In all these situations, it might not be possible for power company repair crews to work, and this will delay the power restoration effort.

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

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.

8. Design Considerations

For low voltage distribution systems, design recommendations to reduce future damage in areas not prone to liquefaction or landslide include: add wind spacers to overhead primary wires; add slack to secondary wires; use high toughness composite insulators; automatic switching of circuit breakers at substations upon sensing high S-wave motions; use underground secondaries; use 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 use of reinforcement within the concrete duct banks can provide additional protection in liquefaction and landslide and fault offset zones.

9. Conclusions

As of 2016, the California Public Utility Commission General Orders do not require seismic design for power distribution systems. The findings herein can be used to develop seismic guidelines for overhead and underground electric distribution systems, with focus on: how transformers should be bolted to power poles; underground cable installations; suitable slack (and sag) to prevent excessive wire impact forces on pole, cross arms and related hardware; real-time isolation to prevent contact burns; use of spacers to prevent wire wrapping.

Ever since the 1952 Taft earthquake, PG&E has taken steps to directly anchor distribution transformers to poles throughout its service area. In the 2014 Napa earthquake, no power poles “fell over” and no transformers "fell off power poles". The most common seismic vulnerabilities in Napa were due to a combination of cable dynamics and wood degradation over time, which resulted in damaged cross arms and related hardware; and sometimes to wire wrapping and / or contact burns.

Fragility models for overhead and underground distribution circuits are presented in this paper and are based on the observations in the Napa earthquake. These allow forecast of damage due to shaking and well as PGDs due to liquefaction, landslide or surface faulting.

The promising findings are that PG&E has already taken some prudent actions to reduce major damage to low voltage power distribution systems, in part based on lessons learned form the 1952 Taft earthquake. The same cannot necessarily be said of all other power companies. There remains much work that can be done to further reduce the potential for power outages, and with diligent application, the remaining weaknesses can be largely mitigated over the next decades.

10. Abbreviations and Units

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

11. References

[1] Eidinger, J (editor), Kwasinski, A., Yashinsky, M., Andrew J., Schiff, A. Tang, A., South Napa M 6.0 Earthquake of August 24 2014. Rev. 2.

[2] Eidinger, J., Kempner, L., Performance of Buried High Voltage Power Cables due to Earthquake Loads, presented at CIGRE, Auckland 2013.

[3] G&E, Seismic Fragility Formulations for Water Systems, Report 47.01.01 Rev. 1, July 12 2001.

All references available at http://www.geEngineeringSystems.com