RESILIENCY OF POWER GRIDS AFTER EARTHQUAKES

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Abstract

A vital aspect on the restoration of civilization to good working order after earthquakes is the restoration of the power grid. 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 describes the performance of Pacific Gas and Electric's (PG&E) low voltage distribution system in the 2014 Napa earthquake. The paper examines what was the actual damage that caused power outages, what level of effort was needed to make repairs, and describes fragility models that can forecast this damage. The paper extends these findings to provide a forecast of power outages for future large earthquakes on the San Andreas fault near the City of San Francisco.

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. 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 (a "customer" is a billing account), Figure 1. See Eidinger et al (2014) for a detailed 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.

Table 1 lists the lengths of all the low voltage distribution feeders in Napa County. Not included in these lengths are the secondary conductors that take the power from the feeder circuit to transformers and then to individual customers. The populations in Napa based on the 2013 - 2014 census data was 141,667 people.

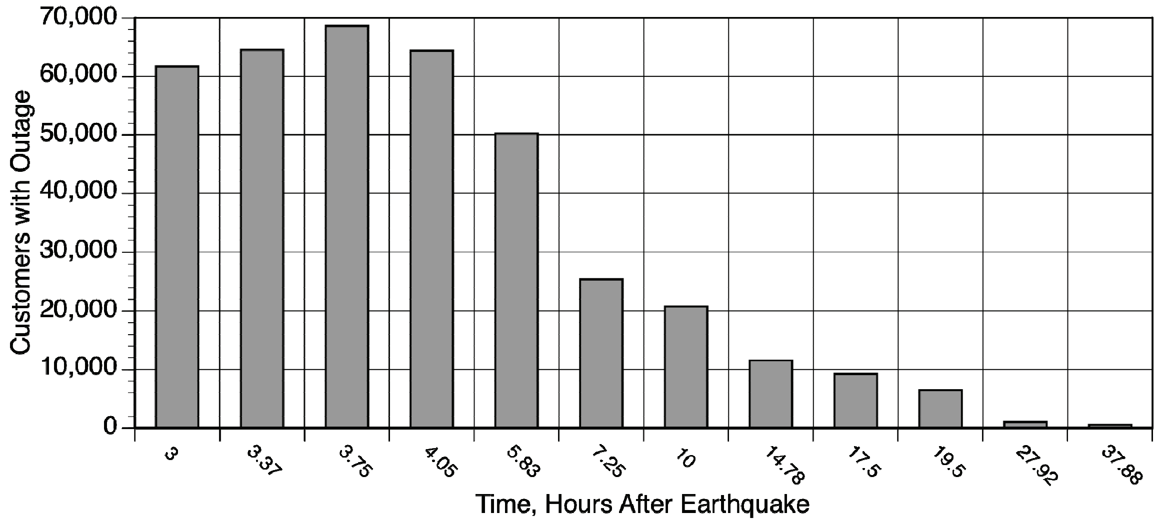

Figure 1. Power outages.

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

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.

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 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.

In the Napa 2014 earthquake, power was available at all times at all high voltage transmission substations. All outages were caused by damage in the distribution system. Table 2 shows the total repair effort was 4,478 manhours, or an average of 35 manhours per repair. About half of the total effort is assigned to the category "Logistics", which is the labor effort to provide in-office coordination. 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.

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).

We correlated the damage to the distribution system, relative to the levels of exposed hazards. Using this data, 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).

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

Figure 2 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 Figure 2; 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 ~10 to 20 cm of PGD.

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 (~2,400 km) 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, each segment being an average of about 100 meters long) to assign to each segment the five seismic hazards. We then aggregated the known repairs and the length of feeder circuit in each hazard value bin.

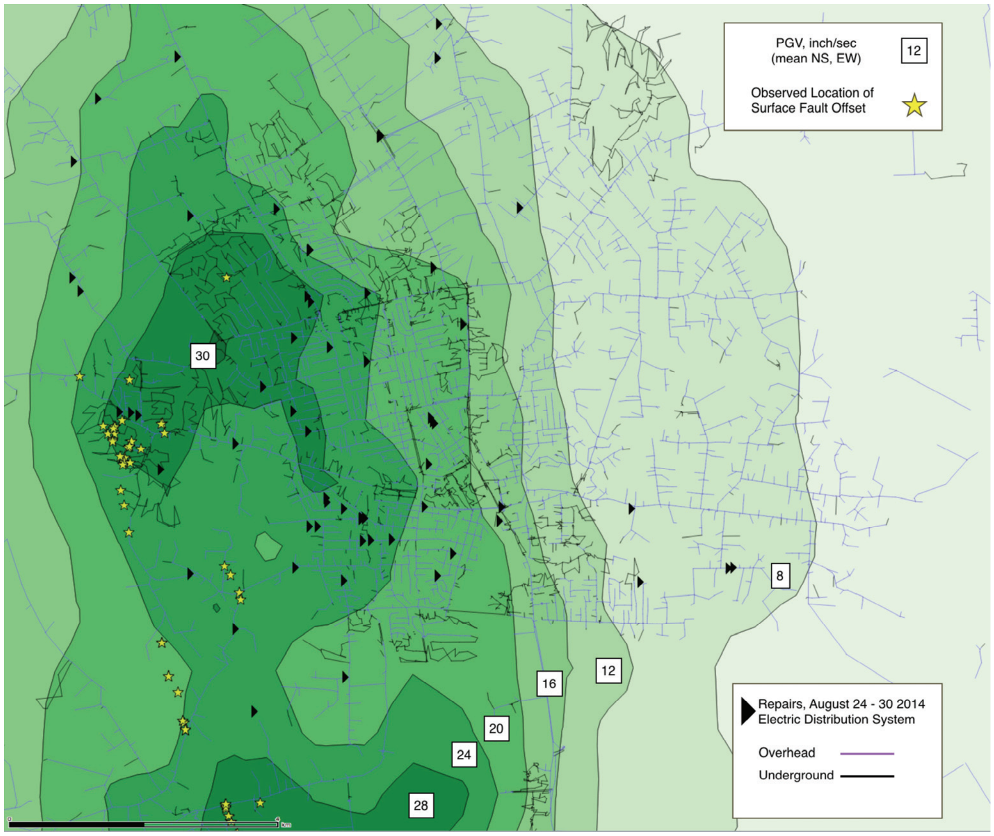

Figure 2. Electric distribution system repairs near the city of Napa.

The results using PSA(T=3.0 seconds) are presented in Figure 3. There is a clear trend of increasing repairs with increasing seismic hazard. The regression R^2 value for PGA (0.24) was much lower than for PSA(T=3) (0.96). This suggests that PGA is not a very good a predictor. Mostly, we think that the better goodness-of-fit for long period motion is because the overhead poles and wire systems are long period structures and the level of damage is largely tied to the differential movements between overhead poles that leads to 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). 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 PG&E's wind-related design of wood poles 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 5° to 10°, but none fell over, and these tilts were not sufficiently severe as to cause faults or warrant immediate replacement.

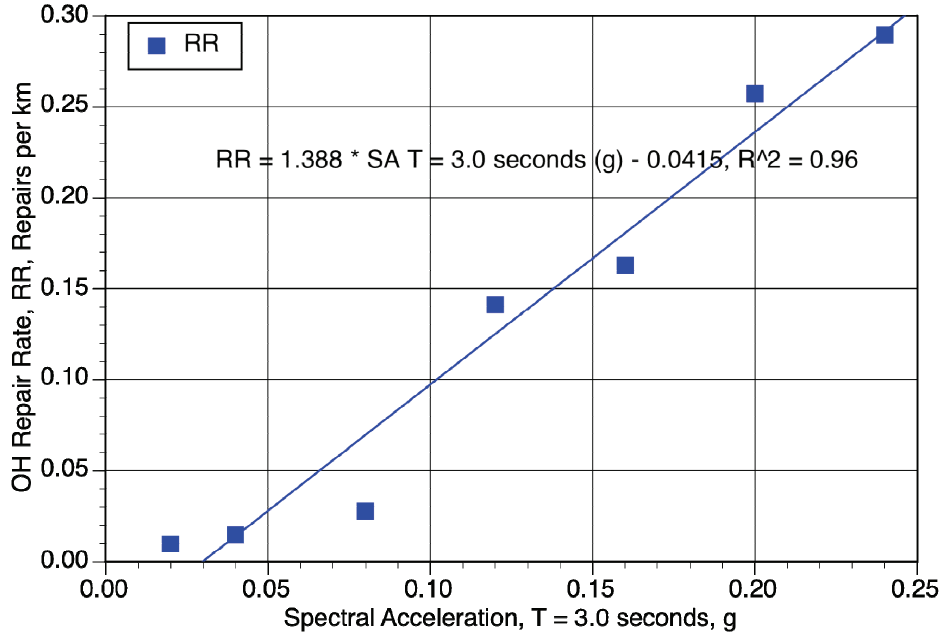

Figure 3. Repair rate, overheads, using PSA (T = 3.0 seconds).

Fragility Models

We processed the damage data for PG&E's system in Napa to develop fragility models for overhead distribution systems. For underground systems, the models factor in the performance of PG&E's underground cables (generally constructed in ducts) as well as Orion's (Eidinger, Kempner 2013) underground cables (generally constructed by direct burial).

Table 3 and the following formulae provide the recommended fragility models for PG&E's overhead and underground distribution components for inertial shaking.

Table 3. Repair Rate, due to Shaking

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 undergrd. 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

Note: k1 reflects the type of construction of primaries. k2 reflects the type of construction of secondaries. k3 is a factor for age effects: 1.25 if year of construction is 1945 or earlier; 1.0 if 1946 to 1990; 0.80 for 1991 or later.

Cases 1, 2. (Overheads).

$$RR_{shake} = k1 \times k2 \times k3 \times \left(1.388 \times PSA_{T=3.0} - 0.0415\right), PSA_{T=3.0} \geq 0.03g;\ \text{0.0 otherwise}$$

Cases 3, 4 (Underground). The damage rate is proportional to strain induced into the duct. Prior work (G&E 2001) shows that the repair rate of buried pipes (and cables) is directly proportional to ground strain, which in turn is proportional to PGV.

$$RR_{shake} = k1 \times k2 \times k3 \times 0.00187 \times PGV$$

where RR_{shake} is repairs per km, PGV in inches/sec, and k1, k2, k3 are from Table 3.

The damage rates for feeders due to liquefaction and landslide are described in Table 4. The repair rate model is:

$$RR_{liq} = k1 \times k2 \times k3 \times PGD^{1.1245}, \text{ PGD > 0.5 inches}$$

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

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

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

Case	*k1*	*k2*	*k3*
1. Overhead primaries and secondaries	0.00125	1.0	0.8 to 1.25
2. Overhead primaries, UG secondaries	0.0025	1.0	0.8 to 1.25
3. Underground in non-filled duct	0.01	1.0 (duct has no reinforcement) 0.125 (duct has 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

Note: k1 reflects the style of construction. k2 reflects the style of reinforcement. k3 is age effects, as above.

Repair Logistics

One of PG&E's post-earthquake activities is to repair the damage in order to restore power to customers, in a safe manner. The logistics to make the repairs includes the following. Identify from customer feedback or direct observation by a PG&E crew 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. Locate the damage for overheads by visual observation and undergrounds using specialized test equipment. Back-office efforts by the power company are also needed to provide the necessary coordination for all these activities.

Power Outage Forecasts for San Francisco

Using the fragility models outlined in this paper, we forecast the potential for power outages for the City of San Francisco due to damage to the electric distribution system. The power grid for San Francisco, includes 1,838 km of distribution feeders, 261 feeder circuits, and serves 400,855 customers. We ran a suite of possible earthquakes, including San Andreas events from magnitude 6.0 to 8.0 in 0.2 magnitude intervals, as well as two historic earthquakes for calibration: the 1989 M 7.0 Loma Prieta and 2014 M 6.0 Napa earthquakes. Using the fragility models outlined in this paper, there are essentially no power outages forecast within San Francisco for the two historic earthquakes. Of interest are the "best estimate" forecasts for power outages in three large earthquakes: M 6.6, 7.0 and 8.0 events that all rupture the nearby Peninsula segment of the San Andreas fault. The chance of power outage at 13 selected water pump stations are listed in Table 5.

Table 5. Chance of Power Outage to Water Pump Station

Water Pump Station	*M 6.6*	*M 7.0*	*M 8.0*

Allemany	27%	60%	74%
Bay Bridge	2%	10%	70%
Central	7%	26%	60%
Clarendon	18%	55%	75%
Crocker Amazon	9%	31%	52%
Forest Knolls	3%	12%	30%
Lake Merced	5%	18%	37%
Lane Street	22%	51%	65%
Lincoln Park	14%	50%	78%
McLaren Park	27%	60%	74%
Summit	12%	38%	66%
AWSS PS 1	1%	4%	69%
AWSS PS 2	4%	12%	39%

The large variation in chance of outage at each pump station reflects the style of construction of the feeder circuit serving each specific pump station, the length of each circuit that traverses liquefaction or landslide zones, and the varying level of shaking along each feeder circuit. The amount of PGDs due to liquefaction and landslide will increase substantially with increasing magnitude and duration of shaking. While the Napa earthquake showed that common installations can accommodate 10 to 20 cm of PGD, considerable damage is still expected at PGDs that exceed 1 meter. Other factors that will contribute to actual power outages include concurrent damage to the PG&E transmission system serving San Francisco (not addressed in this paper), and emergency response actions that might occur, such as requiring power to remain turned off until inspections for gas leaks or other issues are resolved.

The duration of power outages for specific customers will depend, in part, upon where PG&E elects to initially assign its repair crews. Assuming repair crew sizes of 250, 500 or 1,000 people for the M 6.6, 7.0 and 8.0 earthquakes, the estimated time needed to restore power to all essentially all customers in San Francisco is 0.6, 2.1 and 13.6 days, respectively. These outage times could be shortened if there is less damage or if more repair crews are available.

Conclusions

Fragility models for overhead and underground distribution circuits were developed 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. These fragility models were then used to forecast power outage probabilities and durations for each water pump station in the City of San Francisco.

The promising findings are that PG&E has already taken some prudent actions to reduce major damage to low voltage power distribution systems over the past 60 years. Even so, 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.

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).

References

The references are available at: http://www.geEngineeringSystems.com.

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