Water - Power Lifeline Interaction

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Abstract

The interaction of water and power lifelines is described in three modes of operation: normal, fire and earthquake. Case study applications will be taken from large water and electric lifelines serving the greater San Francisco Bay Area operated by East Bay Municipal Utility District (water) and Pacific Gas and Electric (electricity).

Two emergency events are examined: the recent 1991 Oakland Hills firestorm and a future Hayward Magnitude 7 earthquake. Both the water and electric lifelines have limitations under these emergencies that will hamper provision of lifeline services to end users of water and electricity. A model is presented to deal with the interactions between these utilities. By using this model, the water utility can plan for a reasonable number of backup power / pumping units to deal with these types of emergency events.

Fire Exposure

The PG&E and EBMUD lifelines discussed in this paper are located east of the San Francisco Bay, locally called the East Bay area. The East Bay area examined in this paper includes 22 communities with a population of over 1,200,000 people.

The East Bay area is exposed to a number of fire risks. A "normal" fire is one which consumes a single structure or small group of structures, but which does not spread past the immediate fire ignition area. The area has two additional exposures to fires which are not "normal". First, about 20% of the populated East Bay area has been

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built in what is commonly called an "urban intermix" environment. An urban intermix environment is an area where constructed facilities have been built within rural heavy fuel load zones. The Berkeley - Oakland Hills area has averaged one wildland fire every five years over the past 70 years. Several of these fires consumed multiple constructed facilities. The two most damaging fires were the 1923 Berkeley Hills fire (600 dwelling units burned) and the 1991 Oakland Hills fire (3,000 dwelling units burned).

The second "non-normal" fire exposure in the East Bay area is a Fire Following Earthquake (FFE). An earthquake on the Hayward fault will cause fire ignitions in the East Bay area. Various factors, including loss of PG&E electric power, can result in lack of fire fighting response to every fire ignition, possibly leading to fire spread.

Earthquake Exposure

The Hayward fault runs directly through the EBMUD service area. Current best estimates [USGS] suggest that the Hayward fault will produce a magnitude 7 earthquake with a 28% probability by the year 2020**.** The EBMUD service are is also exposed to substantial hazards from other nearby faults. The EBMUD and PG&E systems were evaluated for several earthquake scenarios: the scenarios are deterministic in magnitude and are otherwise treated in a probabilistic manner. Uncertainties in ground motions, equipment responses, and system responses are considered by running multiple simulations of each scenario earthquake. This paper will describe results for a Hayward magnitude 7 earthquake.

Lifeline Models

Models of the PG&E and EBMUD systems were developed using the SERA (System Earthquake Risk Assessment) code [G&E]. The EBMUD water distribution system modeled includes 3,700 miles of buried pipe, 135 pumping plants, 175 reservoirs, 19 office buildings, 6 water treatment plants, 17 microwave and radio sites, and 20 rate control stations. Potentially vulnerable and vital equipment for each EBMUD facility were included in the model. For example, a typical pumping plant includes a building, several electrically-driven pumps, electrical cabinets including motor control centers, switchgear, etc., and (occasionally) an overhead trolley crane. Local site PG&E equipment (pad mounted transformers, pole-mounted transformers, oil circuit breakers) were modeled. The model included 2,300 individual EBMUD buildings and pieces of equipment. Also, over 300,000 individual pipelines were included in the model.

PG&E's transmission and distribution system in the East Bay was modeled including 28 substations (500 kV, 230 kV, and 115 kV) and 215 local distribution circuits. At each substation, the model included circuit breaker, transformer, air switch, low voltage equipment, ancillary equipment and control buildings. Fragility curves were used to characterize the response to inertial loadings. Recent efforts to upgrade some equipment were included. In total, the model included 1,300 individual PG&E buildings and pieces of equipment.

Past electric system vulnerability studies have concentrated on bulk power using high voltage transmission systems [Ostrom, Matsuda]. This is important for the owner of the electric utility, but does not provide enough information for the water utility to answer: "Will I have electric power at my facilities after the earthquake?" or "How long will the power outage last?" Therefore, the low voltage electric distribution circuits was also modeled.

Empirical evidence shows that low voltage hardware is mostly (but not entirely) rugged. In the current analyses, this lower voltage hardware is explicitly modeled. Most but not all damage to this hardware is easily bypassed shortly after an earthquake. However, 115 kV buried transmission lines crossing the Hayward fault could break due to surface faulting, with repairs taking days. One building housing key transformers could be damaged. Local distribution hardware (poles, transformers, etc. which distribute electricity from the substation to end users) are mostly rugged, but prone to sporadic failures: pole failure due to inertial loading, line failure due to collateral damage to structures which in turn pulls down the above ground poles, and failure of unanchored pole mounted transformers, wire slapping of energized lines. At the water pumping plant site, some transformers were unanchored, possibly leading to slippage and, in some cases, failure.

Water System Dependence On Offsite Power - Normal Operations

The East Bay area is hilly. All of EBMUD's water treatment plants are located between 200 feet and 350 feet above sea level. Water leaving the treatment plants serves about 60% of EBMUD customers through a gravity system (i.e., those customers at lower elevations). For the remaining 40% of customers, water is delivered through a series of pumping plants into 125 separate pressure zones. These pumping plants depend upon offsite PG&E power for normal operations.

EBMUD designs its water distribution system serving hillside communities recognizing that PG&E power may not always be available. Occasional PG&E power outage should not degrade the normal level of potable, industrial and fire fighting water services. To provide reliable water service to customers in gravity zones, electric power is only needed to operate water treatment plants. Since treatment plants have permanent on-site back-up power supply, the interdependency of water and electric lifelines for these customers is minimal.

To provide reliable water service to customers in the pumped zones, electric power is needed to operate the hillside pumping plants. The size (storage capacity) and the demand for water in these pumped zones determine just how dependent the water customer is upon PG&E power.

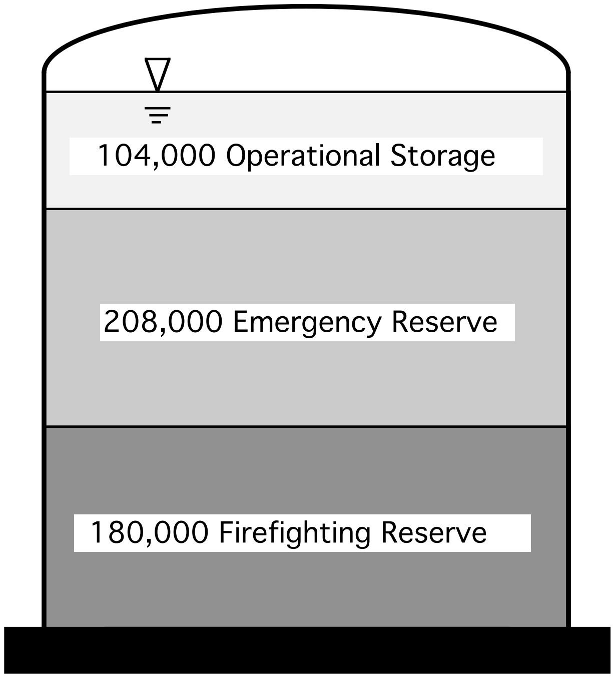

Figure 1. Hillside Tank

Figure 1 shows how the capacity of a 492,000 gallon hillside water tank balances the availability of electric power in providing water service reliability. Hillside tanks are sized using current design philosophy such that three "types" of water are considered: operational storage, emergency reserves, and fire fighting reserves. Operational and Emergency storage is set at 1.5 times the projected maximum day demands. Fire fighting reserve is sized to be able to provide the required fire flows for a particular duration of time. Assuming normal day-to-day operations, a storage reservoir could last 3 to 4 days before it runs empty; however, it is operational policy to keep the reservoirs filled always between 70% and 100% of capacity. Pumping to fill the reservoirs is almost always accomplished overnight, during lower water demand times and lowest cost power time-of-use schedules from PG&E.

EBMUD sizes its pumping plants to be able to fill a reservoir within 16 hours, assuming that the largest individual pump at the pumping plant is removed from service for maintenance reasons. For a typical small hillside pressure zone having a tank with ~500,000 gallons storage, this translates to a reliable pumping capacity of 520 gpm.

In practice, this design approach has shown itself to be extremely reliable. Although a typical customer may experience a few short (a few minutes) power outages per year, and perhaps a major power outage (a few hours) once every one or two years, these types of outages should not lead to loss of water supply to that customer. The reserve capacities in the tanks will provide flows usually for days. And in the extreme case of a very long PG&E outage, EBMUD will have sufficient time to mobilize portable pumps and/or generators to bypass the regular pump station. In practice, this design practice has shown itself to be extremely reliable: other than planned water service interruptions by EBMUD, there have been a few rare cases where customers were inconvenienced because of power outages in the past 10 years (records before 1985 were not reviewed, but no change in trend is suggested).

Further, since the installation of a SCADA system (which can operate without PG&E power), EBMUD operations have been able to track reservoir levels in real time, giving ample warning if a reservoir level falls too low, for whatever reason. With this

SCADA system, usually no actions would be taken for short duration power outages which last up to a few hours. Only when the water demands in the affected pressure zones are extremely high of the water levels become very low in the tanks would backup generators or emergency pumps be moved to the affected pumping plants to replenish the reservoirs. In the past seven years since the SCADA system was operational, customer service interruptions caused by power outages have been non-existent.

Even though EBMUD operates 135 pumping plants, only a very few (2 as of 1994) have permanent backup generators or emergency pumps. For maintenance reasons, and to allow for rare but possibly very long duration power outages, EBMUD maintains 4 portable emergency generators and 11 portable pumps. This amount of portable backup equipment appears to be satisfactory to provide reliable service under normal operations.

The decision to install permanent back-up power supplies at hillside pumping plants is a decision of cost versus reliability. Customers are always conscious of water rates. The cost to install a permanent backup power supply / pump at every pumping plant would be about $24,000,000, and an annual operating cost of about 10% of the capital cost. This high level of expenditure would appear unwarranted, as service levels under normal operations are already adequate.

Water System Dependence On Offsite Power – Fire Conflagration

The October 20 1991 Oakland Hills fire destroyed over 3,000 dwellings, and was the most devastating urban–wildland intermix fire which has occurred in the United States. These intermix fires differ from “normal” fires in terms of water demands required for suppression. First, because of the geographic size of intermix fires, the total fire flows will be *much* larger than for normal fires. Second, intermix fires will usually involve many pressure zones. Third, intermix fires are likely to occur in portions of the EBMUD service area where development density is relatively low and capacity of the water distribution system to supply high fire flows is much more limited than in higher density developed areas. These three attributes of intermix fires combine so that such fires will place water demands which cannot be met by a system designed only for “normal” fires.

A study was performed of the actual power and fire fighting water usage during the 1991 Oakland Hills firestorm [VSP et al]. Eleven pumped pressure zones were simultaneously involved in providing fire flows. The typical reservoir supplied about 6,000 gpm during the period of peak fire fighting activities, or 4 times the de-facto 1,500 gpm fire flow requirement. Figure 2 traces the usage of water during the course of the fire. The fire started to spread at about 11:00am. Up to that time, water usage in the area was about 5,000 gpm, reflecting normal early Sunday morning consumption. Fire flows increased to over 25,000 gpm during the time of peak spreading of the conflagration (around 1:00pm). Fire flows dipped to about 18,000 gpm at 3:00pm, and then stabilized at 25,000 to 30,000 gpm from 5:00pm and overnight. The fire spread was stopped at about 5:00pm on October 20, 1991. The high rate of usage overnight reflects fire fighter activities to contain the fire and water lost through open service connections.

PG&E power was lost to nine different EBMUD pumping plants during the fire. Outages occurred starting at 11:35am October 20, 1991. Some reasons for the PG&E outages were burnt power poles and conduction of heat through conduits to underground PG&E distribution circuits. PG&E restored power to three largest and lowest elevation pumping plants at 5:46pm October 20, 1991, by stringing new wires to these pumping plants (the zones served by these pumping plants never ran out of water during the fire). Access to the pumping plants were limited due to heat and fire, and EBMUD crews were unable to put portable emergency generators in place at these three pumping plants prior to PG&E restoring offsite power. At one higher elevation pumping plant, two portable pumps were installed by 3:00pm October 20. All remaining pumping plants had emergency generators or pumps in place by 2:30pm October 21. PG&E power was restored to all pumping plants by October 25.

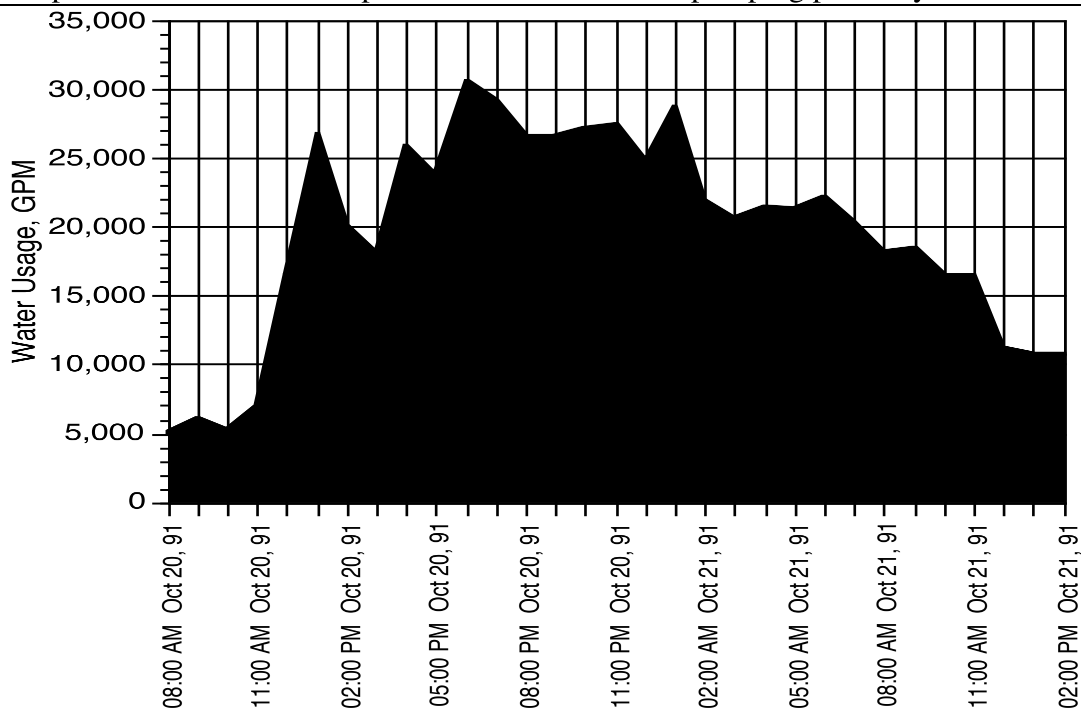

Figure 2. Water Flows During 1991 Firestorm

The lessons learned from the Oakland Hills firestorm with regards to the interrelationship of water and electric lifelines are as follows:

1. Fire flows in pumped pressure zones were initially delivered from in-zone tank storage. Actual fire flows greatly exceeded the design flows.

2. The loss of offsite power and the lack of on-site emergency backup power prevented pumping plants from replenishing reservoirs. However, pumping plant

design capacities in most pressure zones were less than 1,000 gpm. Had power been available, these pumping plants would have been able to only incrementally add to total fire flows delivered (about 5% extra total water). In most areas, water delivered to one zone would have been at the expense of water removed from the lower zone.

3. Once reservoirs in lower zones were emptied, pumps in higher zones would likely have been unable to draw water from lower zones, even if power had been available to the pumping plants.

4. Oxygen starvation during a major conflagration may stop backup diesels from operating.

5. The reliability of backup diesel driven pumps is not 100%. Excluding operator error, seismic damage or oxygen starvation, backup diesels fail to operate on demand about 3% of the time. (After strong ground shaking, reliability is much lower).

6. Emergency portable equipment (pumps or generators) can be mobilized and put into service in a few hours.

The 1991 Oakland Hills was a "beyond design basis" fire. Fire flow demands greatly exceeded the 1,500 gpm design basis. The design of the water system would not have allowed much increased fire flows even if power had been available. Recent studies have shown that the upgrades to the water distribution system to combat this type of firestorm would involve the addition of large reservoirs at the top elevation of each chain of pressure zones, with pressure regulators to allow access to this water in the lower zones. This type of upgrade is more reliable than the addition of emergency backup power supplies and increased sizes of pumping plants. The cost of such upgrades, coupled with other factors (water quality, risk of conflagration, etc.) suggest that such upgrades for communities in even high fire risk areas may not be justifiable.

Water System Dependence On Offsite Power – Earthquake

As of 1991, only 2 of EBMUD's 135 pumping plants had permanently installed backup power systems. The remaining pumping plants are dependent upon PG&E power for normal operations. EBMUD currently has enough portable generators and pumps to deal with day-to-day functional emergencies, maintenance and the like (18 units total, of various sizes and designs). Since it is well known that electric systems will have outages due to earthquake damage, there is some question as to whether additional backup power supplies are needed.

The SERA model was used to evaluate the post-earthquake response of PG&E's electric transmission and distribution systems. The model included 28 substations and 215 distribution circuits. Based upon the redundancies in PG&E's system, the reduced power demands in a post-earthquake environment, and PG&E's ability to repair damage, the expected duration of power outages was calculated. About 65% of the area was expected to be black immediately, reducing to 50% (1 day after the earthquake), 20% (2 days) and 3% (3 days). (There is variability in location and duration of outages).

The number of pumping plants were calculated by exposing PG&E's electric systems to a number of simulations of the Hayward magnitude 7 earthquake. While variabilities guarantee that different outcomes of post-earthquake outages can occur, the following trends are observed:

1. About half of EBMUD's pumping plants will lose power after a Hayward magnitude 7 earthquake. No single failure of a PG&E substation affects all of EBMUD's pumping plants.

2. Longest outage durations for most pumping plants are expected to be on the order of three days. Many will have power restored in less than two days.

3. PG&E's substation network in the immediate East Bay area does not include any 500 kV substations which are particularly prone to damage. There are multiple power transmission paths into the East Bay area both to 230 kV and 115 kV substations, and generation capacity will not be severely limited by the earthquake. This network redundancy helps limit how widespread the outages will be and the duration of outages.

4. The most vulnerable aspects of PG&E's substations (live tank circuit breakers) have mostly been replaced in the East Bay area. PG&E's more vulnerable 230 kV transformers are being upgraded. PG&E has already upgraded some of its control buildings.

Within several hours after an earthquake, EBMUD can mobilize emergency equipment to provide pumping / power for about a dozen pumping plants. However, not all remaining pumping plants need such emergency equipment to be immediately on hand for the following reasons:

1. Some pressure zones have adequate water storage to last until PG&E restores power. These zones are characterized as having large reservoirs, are mostly located in the outer reaches of EBMUD's service area away from the Hayward fault, and not prone to substantial damage to buried pipe.

2. Additional emergency equipment can be procured through mutual aid agreements with agencies located outside the sphere of damage from the Hayward Magnitude 7 earthquake.

3. Some pressure zones have multiple pumping plants. Barring a large number of fires following earthquakes, emergency power may not be needed at all pumping plants.

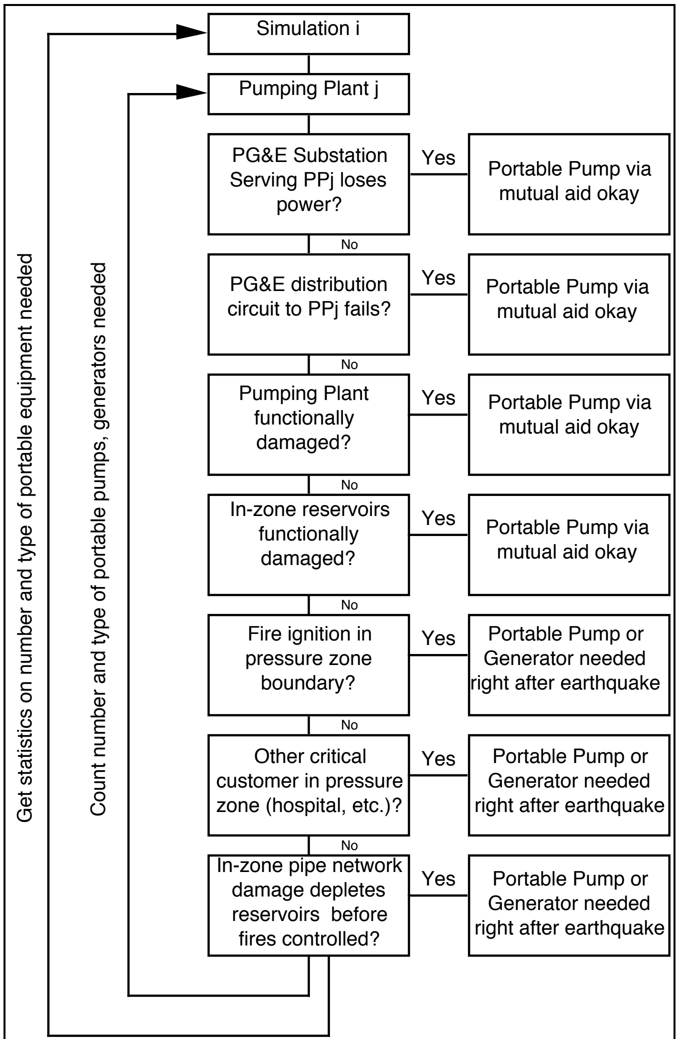

Figure 3. Logic for Portable Pumps and Generators

Number of Portable Pumps and Generators

Figure 3 shows the logic considered in assessing how many portable pumps and generators are needed. By running through this logic for a number of simulations, one develops the number of portable pieces of equipment needed to have on hand immediately after the earthquake, and the number of pieces of equipment which can be procured through mutual aid. (All cases where PG&E power is available not shown). For EBMUD, about 22 pieces of equipment are needed immediately, which is far less than the total theoretical upper bound. This results in cost savings, if one is willing to let some customers have no water until either PG&E power is restored, or sufficient portable pumps / generators are mobilized through mutual aid (perhaps 2 - 3 days after the earthquake). This would appear a reasonable policy.

References

Probabilities of Large Earthquakes in the San Francisco Bay Region, California, U.S. Geological Survey Circular 1053, 1990.

Ostrom, D. K., "Understanding the Earthquake Environment, Corporate Strategies," Proceedings of 3rd U.S. Conference on Lifeline Earthquake Engineering, TCLEE Monograph No. 4, August 1991.

Matsuda, E., Savage, W., Williams, K, Laguens, G., "Earthquake Evaluation of a Substation Network," Proceedings of 3rd U.S. Conference on Lifeline Earthquake Engineering, TCLEE Monograph No. 4, August 1991.
G&E Engineering Systems, "Seismic Evaluation Program, Final Report," prepared for EBMUD, January, 1994.
Geomatrix Consultants, "Phase IB Geotechnical Assessments for EBMUD," Report 23012, May 26, 1993.
East Bay Hills Firestorm Response Assessment, Phase I Final Report, Prepared for EBMUD by VSP Associates, G&E Engineering Systems, and BF Associates, July 1992.