Fire and Economic Impacts of Earthquakes

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Abstract

This paper describes two types of losses due to disruption of lifeline service following an earthquake. These are fire and economic losses. Highlights of the fire following earthquake and economic models are described, followed by case study analysis for the twenty two city area in the East Bay region of the San Francisco Bay Area.

Fire Following Earthquake Model

A computer model is developed for prediction of fire losses in communities due to fires following earthquakes (FFEs). A comprehensive treatment of this model is described in [Eidinger and Dong]. The model includes the three stages of FFEs: Ignition, spread and suppression. A synopses of the model follows:

Fire ignitions. The number of fires that start (ignite) following the earthquake is determined. The model is based upon the empirical evidence of 30 U.S. cities in 10 past earthquakes [Eidinger and Dong]. The following ignition model is developed:

$$\text{Ignition Rate} = -0.025 + (0.59 * PGA) - (0.29 * PGA^2)$$

where Ignition Rate is the number of ignitions per 1,000,000 square feet of built up structure and PGA is Peak Ground Acceleration (horizontal). Approximately 50% - 75% of the ignitions occur immediately after the earthquake, with the remaining ignitions generally occurring within 24 hours after the earthquake.

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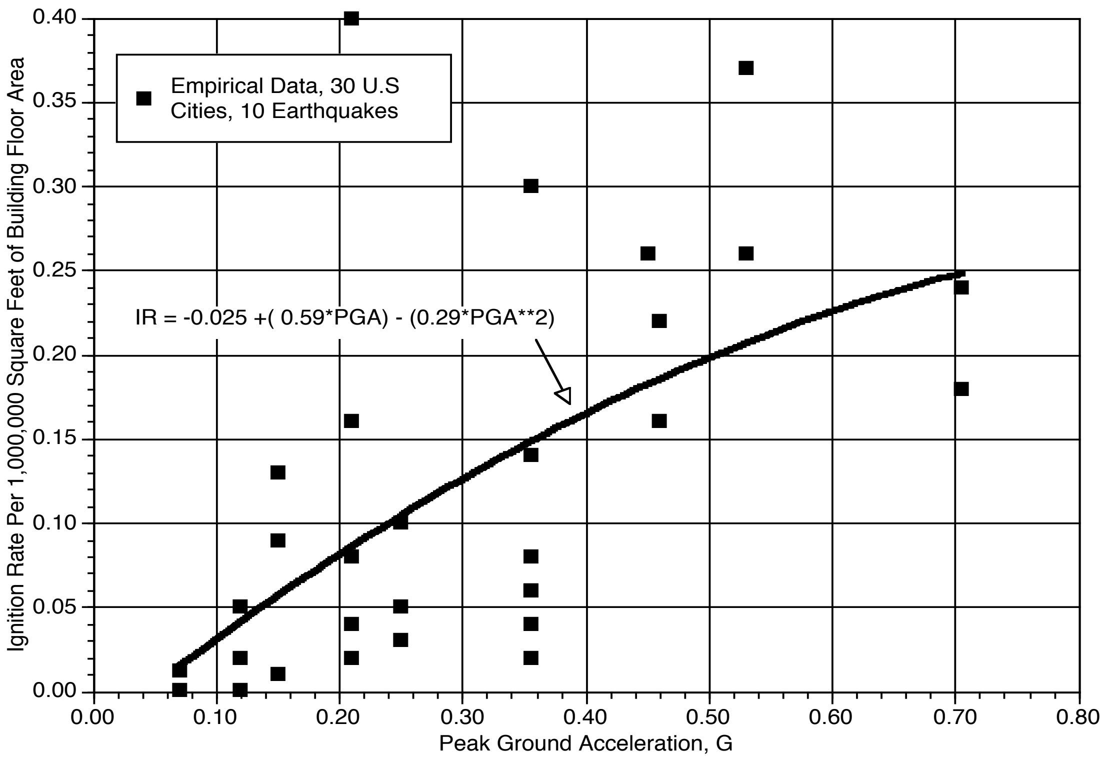
These ignitions stem from all sources common to typical California cities. The model can be refined to differentiate the number of ignitions as a function of PGA and permanent ground deformation (PGD), as PGD has a major role in predicting breakage to underground gas pipelines (a fuel source) and water pipelines (key to fire suppression). The model can also be refined to account for areas where substantially different construction types, fuel sources, industrial make-up, etc. would differ. If an area had no natural gas distribution system, then a portion of the fires would not occur. If an area includes many oil furnaces, propane tanks, etc., then the ignition rate will be higher. A key aspect is the large uncertainty bounds, and deviations much above the median can often lead to huge increases in fire losses, if suppression resources are constrained.



Fire spread. The fire spread model is based upon the application of the Hamada model. Empirical bench marking of the spread model includes new data from the well documented 1991 Oakland Hills fire, including the effect of wide firebreaks (such as the 8 lane freeway and the 4 lane freeway firebreaks which that fire crossed).

$$N_{t,V} = f[c * K_s * (K_d + K_u)],$$

where $N_{t,V}$ = Number of structures fully burned, as a function of time t, minutes, and wind speed V, meters/second, and c is a constant which is a function of building density, fire break sizes, and varies throughout the are being studied. A complete discussion of the model can be found in [Eidinger and Dong], [Scawthorn] and [Hamada]. The main points of the equation is that the area burned is represented by the $K_s * (K_d + K_u)$ term, where each K factor is calculated as a function of wind speed, fire break sizes, materials of construction (collectively, the spread rate).

Fire suppression. The fire suppression model incorporates the number of fire apparatus available, the fire report time, apparatus travel times, as well as a detailed model of available water for fire flows. The fire department response activities (staging of equipment and personnel) used in the current study is adapted from [Scawthorn]. A new model to examine the role of water availability, over time, at the scene of a fire is incorporated into the suppression model. In the case study described below, the availability of water is calculated as a function of time after the earthquake, for each of 125 pressure zones throughout the East Bay Municipal Utility District (EBMUD) service area, the water utility that provides water to all 22 cities studied. Damage leading to loss of water (broken pipes, draining of tanks, loss of electric power at pump stations) all leads to a reduction of water supply, in hard hit areas, worsening as time passes after the earthquake; however simultaneously, the benefits of emergency response activities (valving out broken pipes, installing portable generators and pumps, use of above ground portable hose) is also credited for improving water supply over time. Constraints in post-earthquake emergency response (time to mobilize people to get things done) is a critical factor in how fast water supply can be provided to fire scenes. Two of the parameters used in estimating fire suppression effectiveness are:

- How much water is needed at the fire scene, given the current size of the fire? The following model is used in residential areas:

  $$W_t = 1,250\ (N_{tV})^{0.4}$$

  This model says that if $N_{tv} = 1$ (one fully involved single family structure), the water needed to control the fire is 1,250 gpm. The model provides a transition from a flow needed of 500 gpm (generally satisfactory if the fire still has only burnt a part of the structure, and a general minimum suggested by the Uniform Fire Code), to as much as 30,000 gpm, for a widespread conflagration of 3,000 structures (based on water usage trends in the 1991 Oakland Hills fire [Eidinger 1993]. R_{water} is then set as the ratio of the water available at a fire divided by the water needed at a fire.

- How many fire trucks (and attendant fire fighting personnel) are needed at the scene of a fire, in order to control its growth? In a post-earthquake environment, the fire department will have many demands for services other than just fire fighting (eg., urban search and rescue). R_{truck} is then set as the ratio of the number of fire trucks available at a fire divided by the number of fire trucks needed at a fire.

These two needs (water and fire trucks) are combined to recognize that the effectiveness of fire suppression activities is a combination of these two factors:

$$P_{effective} = (R_{truck} * R_{water}) ** 0.7$$

This model allows that there is zero effectiveness if there are no fire trucks (proxy for all suppression activities) at the fire scene. If there are fire trucks available, but no water (not uncommon after an earthquake), then $P_{effective}$ is judged to be 0.25.

Finally, the fire Spread Rate (ΔK_s, ΔK_d, ΔK_u over time) is slowed down or halted, considering suppression activities. The following algorithm is used:

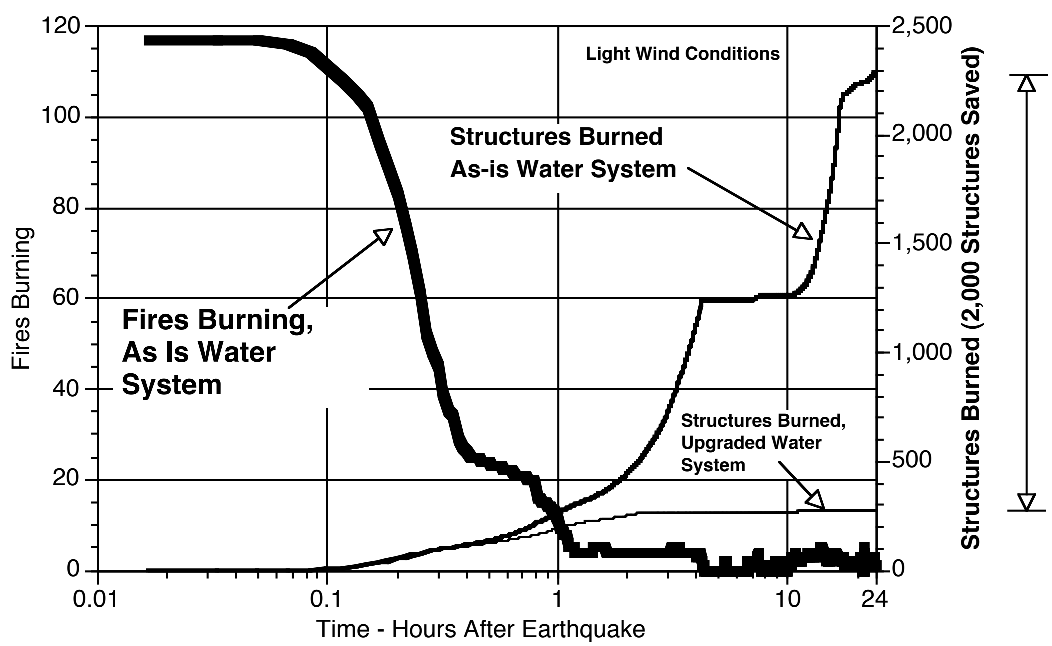
$$\text{Spread Rate} = \text{Spread Rate}_{non\text{-}suppressed} * (1 - P_{effective}^{0.7}).$$

Case Study

The model is used to study the potential reduction in the number of structures burned in the 22 city area served by EBMUD, under various earthquake, wind and water system improvement scenarios. The figure below shows a typical set of results.

This figure is interpreted as follows:

- The left axis (Fires Burning) shows the number of fires simultaneously ongoing after the earthquake. For example, at time 1 minute, 117 fire ignitions occur. The thick-lined curve shows that none of these fires come under control for the first few minutes (the curve is flat).



- By 0.1 hours after the earthquake, some of the fires have been detected and controlled. Within 0.3 hours after the earthquake, about two thirds of the initial ignitions are controlled. By this time, about 100 "equivalent" structures are burned, independent of whether the water system is "seismically-upgraded" or not. That is to say, on average, each initial serious ignition has burned 1 structure. In practice, many of the ignitions will have burned considerably less than 1 structure (perhaps just a room within a structure), but some of the ignitions will have spread and burned some adjacent structures.

- Between 0.3 hours and 0.8 hours, a few more of the remaining ignitions are controlled, leaving about 20 fires still uncontrolled at 0.8 hours. This reflects that some of the more stubborn fires are taking considerable more fire department resources, which take time to mobilize. Also shown is that the number of structures burned under the two water system scenarios (as-is, or seismically upgraded) are beginning to diverge. This indicates that under the "as-is" scenario, at some fire locations the lack of water supply is hampering fire department suppression capabilities, allowing those fires to spread to more structures.

- At about 1.2 hours after the earthquake, the number of fires burning assuming the as-is water system (thick curve) ranges between 4 to 5, until 4 hours after the earthquake. (The number of fires can increase, as new ignitions continue to occur after the earthquake.) (Note: for the upgraded water system, the Fire Burning curve goes to zero at about 2.5 hours, with occasional new ignitions showing up thereafter, which are all quickly controlled.)

  From time 1.2 hours to 4 hours, the uncontrolled fires are spreading, and burning many structures (i.e., there are 4 conflagrations ongoing). At 4 hours after the earthquake, all of the fires are controlled, and the number of structures burned "plateaus" at about 1,250. Between 4 to 10 hours after the earthquake, a number of ignitions start, but these are relatively quickly controlled, and few additional structures are burned. In this particular simulation, at time about 12 hours, a fire starts, and due to lack of water at the fire site, high fuel load, etc., the single ignition quickly spreads into another conflagration, burning another 1,000 structures.

- In running the model for many simulations, the sensitivity to the total number of structures burned at time 24 hours was often directly linked to the lack of water at a fire site, for a fire that ignites 6 to 18 hours after the earthquake. The areas particularly prone to such lack of water in the EBMUD service area are those areas in hillside communities, where lack of pumping (power outages, equipment damage) hamper rapid restoration of water supply; pipeline damage leads to draining of existing undamaged hillside tanks faster than crews can be mobilized to find and isolate broken pipes; and damage to hillside tanks (elephant foot buckling in steel tanks, foundation damage in concrete tanks, etc.) leads to rapid loss of water inventory within 4 hours after the earthquake.

Over 500 simulations of the model were run to examine the uncertainties in the various factors in the model, earthquake hazards, etc. The following table provides summary insight as to the effectiveness (costs of seismic upgrades, and fire losses, millions of dollars, upgrade costs shown in bold, all values in millions) if water systems are upgraded to be more seismically resilient.

Scenario Earthquake	**Level of Improvements to Water System**				
Wind Velocity	**As Is**	**$13 M**	**$16 M**	**$84 M**	**$202 M**
Hayward M-7					
calm	$140 M	$125 M	$120 M	$100 M	$55 M
light	$330	$280	$265	$165	$120
high	$1,860	$1,840	$1,835	$1,805	$1,630
Calaveras M-6.75					
calm	$10	$10	$10	$9	$7.6
light	$20	$19	$19	$18	$14
high	$260	$240	$235	$195	$180

The following observations are made:

- Upgrades to the water system significantly minimize fire losses in the larger magnitude (more damaging) earthquakes. This is reasonable. For example, the model correctly predicted that there would be under $1,000,000 in fire damage from a repeat of the 1989 Loma Prieta earthquake. Basically, in small earthquakes, the fire department resources, even with a slightly damaged water system, are found to be sufficient to control all fire ignitions, with not much worse response than under normal non-earthquake conditions.

- Upgrades to the water system have great beneficial effect if the winds are calm or light at the time of the earthquake (the prevailing wind conditions more than 90% of the time).

- If winds are high (over 10 m/s), the potential for multiple conflagrations is very high, even if the water system were in perfect undamaged condition. In part, this is because the water system is not designed to provide extremely high flow rates in residential areas (over 10,000 gpm), as the modern UFC code only requires the system to provide on the order of 1,000 gpm in such areas. Due to high winds, at least some of the initial ignitions will spread very fast, quickly outstripping fire department capabilities, and the demand for water in these areas will far outstrip the capacity to deliver the water, even if the system were undamaged.

- If the number of initial ignitions stays below about 1 for every 4,000 structures, existing fire suppression capabilities are sufficient to control most every ignition before substantial spread occurs. (In the current case, about 120 initial ignitions). If, however, just a few more ignitions occur, the "tapped-out" available fire department resources cannot respond, leaving those ignitions unattended, and leading to conflagrations.

The model shows areas where we can become better prepared to deal with large earthquakes in urban American cities. The results show the benefit of upgrading water systems. Other areas which show a lot of promise include emergency preparedness training for citizens to immediately look for and put out fires after the earthquake, before they spread into large fires; pre-earthquake mitigation activities to limit the number of ignitions (bolting down equipment, electricity shut-offs, etc.). The authors note that the cost-effectiveness of distribution or transmission gas shut-off valves remains an open question.

Economic Model

Earthquake damage produces both direct and indirect economic losses. Direct economic losses include not only property damage (buildings, contents, inventory, lifelines) but also the direct loss of functionality arising from physical damage. Direct loss of functionality costs include relocation costs for temporary space, income losses, loss of government services, etc. for those facilities directly affected by physical earthquake damages. Indirect economic losses are secondary losses in economic production, wages and incomes arising from direct physical damages and loss of functionality due to the affected community as a whole which arise because of the direct physical and loss of function impacts on the portion of the community directly damaged by the earthquake.

Direct economic losses are estimated from fragility curves for buildings, contents, and lifelines. Loss of functionality costs arising directly from the physical damages depend on the physical damages are estimated using expert opinion algorithms for restoration times and associated costs developed for FEMA benefit-cost models and NIBS loss estimation models.

Indirect economic losses are much more difficult to estimate because of uncertainty about the impact of earthquake damage on supply and demand by industry sector. Furthermore, the extent of indirect economic losses for an affected region depends on the availability of excess production capability and on the ability to transfer resources between regions. For the EBMUD case study described herein, gross regional products per industry sector were estimated from data in the California Statistical Abstract. Different sectors of the economy have varying degrees of dependence on water supply for the production of goods an services. To estimate this factor, we used the water importance factors given in the ATC-25 report [ATC].

Applying these water importance factors to the gross regional product per day by sector and adjusting for the concentration of economic activity in flatland areas near the Bay, where soil conditions are vulnerable to liquefaction, and thus particularly vulnerable to water outages, we estimate the reduction in Gross Regional Product to be approximately $44,000,000 per day of system-wide water outage. This estimate assumes that the geographically distributed length of water outages affect the Gross Regional Product, on average, in direct proportion to the economic contributions of the industry sectors. In other words, each industry sector was assumed to bear the same fraction of the water outages as its proportion of the Gross Regional Product.

Thus, indirect losses were estimated as the aggregation by economic sector of days of business interruption due to loss of water supply, considering the importance of water supply to production in each sector. Double-counting of production losses due to multiple reasons (building damage, power outages, water outages) was avoided. Indirect economic gains in non-earthuqake damaged areas because any decisions to mitigate against losses due to water outages in order to reduce indirect economic losses would be born solely by the people within the affected area (in this case, the EBMUD service area).

Two caveats should be applied in interpreting these economic estimates. First, the probabilities that the direct and economic losses will occur must be considered. If mitigation measures are under evaluation, benefit-cost analyses should be performed by calculating the net present value of expected future damages and losses to be avoided by the mitigation measures for comparison to the mitigation costs. The frequency of occurrence of losses profoundly affects the benefits of avoiding such losses. For the particular case study being examined in this paper, one should perform such "time weighted" analyses carefully, in that: the occurrence of a major Hayward fault earthquake is almost certainty, and by postponing upgrades today, one is simply shifting the losses to future generations, particularly since the functional lifetime of many utility infrastructure can last hundred(s) of years; the cost of performing pre-earthquake mitigation activities also serves to provide other benefits, such as water quality improvements afforded by replacement of redwood tanks with steel tanks.

Second, the indirect loss estimates discussed above are based on simple assumptions. To the extent that lost production by portions of an industry sector is replaced by additional production from portions unaffected by outages or by increases in production after restoration of services, <u>within the community paying for the pre-earthquake mitigation measures</u>, these losses will overestimate the total indirect economic impacts of the outages.

Case Study

The cities served by the East Bay Municipal Utility District are used as a case study. The post-earthquake damage to the electric power system and water system are first calculated. Then, restoration of water service is developed for each affected region. Following the procedure described above, the indirect economic losses within the communities served by the water system are calculated. The results show the following:

Reduction in Economic Activity within Study Area ($Millions)		
Scenario Earthquake	**Water System - As Is**	**Water System - Upgraded**
Hayward M-7	$1,239	$422
Hayward M-6	$74	$45
Calaveras M-6.75	$62	$41
Concord M-6.5	$22	$11

Conclusions

Two sets of results are presented: first, if the water utility serving the community does nothing (as-is condition); second, if the water utility upgrades its water system in order to mitigate losses after the earthquake. The financial numbers show the following. Without any pre-earthquake water system mitigation measures, there will be $1,569,000,000 losses (fire plus indirect economic attributed to lost water supply), given the occurrence of a magnitude 7 earthquake on the Hayward fault. By implementing a $202,000,000 water supply mitigation program, there will be only $542,000,000 of fire and indirect economic losses. This represents a "payback" ratio of 5. Further benefits accrue due to limit of direct damage, loss of life, etc. Given that a Hayward Magnitude 7 earthquake is currently forecast to occur with a probability of 28% by the year 2020, it is apparent that this type of pre-earthquake investment is worthwhile. When put to the rate-payers through an extensive community outreach program as to their willingness to pay for such a program, about 90% of the responses were positive.

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