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SEISMIC RISK TO LIFELINE SYSTEMS: CRITICAL VARIABLES AND SENSITIVITIES

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SUMMARY

Calculating seismic risk to lifelines requires an accurate description of the system as a function of its components, and of the earthquake threat on faults. Modeling the variability in ground motion is required for an accurate assessment of risk to many lifelines; the particular representation of spatial correlation may be critical in some applications. Spatial correlation of ground motion can be modeled efficiently with simulation by generating a set of correlated ground motion fields for each earthquake. The maximum magnitude is a critical parameter for calculating the risk of rare events; it is less influential if randomness in ground motion is modeled.

INTRODUCTION

An engineering lifeline is a spatially-extended system that provides critical or necessary engineering service to a public or private sector of society. Lifelines are especially vulnerable to earthquakes because of their spatial extent: seismic shocks in a range of locations may damage components of the lifeline and may thus affect its functioning.

A seismic risk analysis of a lifeline assesses the probability that the system might be damaged or lose its function because of earthquakes. Thus we define lifeline seismic risk analysis to mean a representation of: (a) the spatial extent of the engineering system, (b) the distribution of earthquakes in space and size, (c) the effects of earthquakes on system components, (d) the relationship between component damage and system performance, and (e) the probabilities associated with (a) through (d). Many studies have examined the individual elements above, and some have integrated these elements into a statement of losses or damage to lifelines and the associated probabilities.

The purpose of this paper is to examine critical variables in the risk analysis of lifelines, and to draw conclusions regarding which variables are most influential on the probability of loss or malfunction of the system. Understanding the critical sensitivities is important in future research efforts to understand lifeline systems, their vulnerabilities to earthquakes, and ways to reduce that vulnerability.

METHODOLOGY

To quantify the performance of a lifeline system, we define a set of mutually-exclusive, collective exhaustive system states that describe system performance. The earthquake risk to the lifeline is then the probability (typically, per year) that the lifeline is in a system state representing damage or loss. Mathematically this is calculated as:

$$\nu(\text{system state } i) = \sum_j \nu_j \int_m \int_x P[\text{system state } i \mid m, x]\ f_m(m) f_x(x) dm\ dx \quad (1)$$

where ν is the annual rate of being in system state i, ν_j is the rate of earthquakes on fault j, $f_m(m)$ and $f_x(x)$ are probability distributions on magnitude and location for earthquakes on fault j, and $P[\text{system state } i|m, x]$ is the probability that the system is in state i given an earthquake of magnitude m at location x.

The probability of system state i given m and x can be calculated by assuming, without loss of generality, that (a) a system consists of a set of components, and (b) there is a deterministic relationship between the status of each component and the state of the system. The latter assumption could be generalized to a probabilistic relationship, but we have not found any system where, if one knows the status of all of the components, one cannot determine the state of the system. The probability of a system state i thus can be calculated as the probability that the system components fall into such a configuration that the resulting system state is i.

In calculating the response of system components to an earthquake of magnitude m at location x, several variabilities may be important. First, the variability of ground motion amplitude A at each component location is generally large (typically a standard deviation of 60% to 100% of the mean when only the magnitude and distance of the earthquake and the general site geologic conditions are known). We represent this variability as:

$$\ln(A) = f(m, x) + \epsilon \quad (2)$$

where

$$\epsilon = \epsilon_e + \epsilon_d + \epsilon_s + \epsilon_r \quad (3)$$

In equation (3), the residual term ϵ (representing deviations from the mean value) is normally-distributed and is comprised of the sum of four components: an earthquake term ϵ_e, a directivity term ϵ_d, a site term ϵ_s, and a remaining error term ϵ_r. These represent, respectively, the component of ground motion variability contributed by the earthquake source, by directivity of energy from the source, by local soil conditions, and by remaining unknown factors.

The advantage of representing variability in ground motion with equation (3) is that we can easily represent correlation in ground motion residuals between two sites. These correlations arise because the sites are affected by the same earthquake, they may be affected by similar directivity effects (if they are at similar azimuths), and they may be affected by similar soil effects (if they are close to one another). We represent the covariance $\gamma(h, k)$ of ground motion residuals at two sites h and k as:

$$\gamma(h, k) = \sigma_e^2 + 2\ \sigma_d^2 \cos\Theta_h \cos\Theta_k + \sigma_s^2 \exp[-(r(h, k)/r_o)^2] \quad (4)$$

where σ_e^2, σ_d^2, and σ_s^2 are the variances of residual terms ϵ_e, ϵ_d, and ϵ_s, respectively, Θ_h and Θ_k are the azimuths of sites h and k, with respect to the rupture $r(h, k)$ is the distance between the two sites, and r_o is a standard correlation distance. The forms of the terms for directivity and for site effects are reasonable as first estimates of these effects; further discussion of these covariance terms is given in Reference 1. The factor of two in the directivity term ensures that, on average over all azimuths, the diagonal term in the covariance matrix equals the correct total variance of ground motion.

A second important factor in component responses is the variability in component fragility. We define the resistance to ground shaking for each component using an equation analogous to (2) and (3). This allows randomness and correlation among component resistances to be defined and handled analytically in a simple way.

This formulation of lifeline seismic risk is similar to that of (Ref. 2, 3, and 4) in that random magnitudes and locations of earthquakes are considered as the causes of seismic risk, and an integration over all events is performed to calculate risk (probability of loss, damage, or lack of functionality) to the system. Our method is more general than the others, however, in that it handles variability in ground motion, correlation among ground motion residuals at different sites, random component responses (which is also a feature of Ref. 2 and 4), and correlation among component responses. The specific representation of the variabilities and correlations can be modified for specific applications, but the forms described above are adequate for a first examination of the influence of these factors on lifeline risk.

Application of the model is most efficiently achieved by simulating a field of correlated ground motion values, one value at each site, rather than attempting an analytical solution. A set of ground motion values leads to a status for each component, from which the system state can be derived. Simulation of multiple fields of ground motions thereby allows the distribution of system states to be derived for that earthquake magnitude and location. Variabilities in earthquake magnitude and location (the two integrals in equation (1)) are easily treated with numerical integration.

EXAMPLE APPLICATIONS

To investigate the effects of several parameters on lifeline risk, we apply equation (1) to several example problems. The first is a pipeline network problem consisting of a water supply system in east San Francisco Bay (see Figure 1). This problem was first investigated in Ref. 3. The Hayward fault crosses the lifeline; the rate of seismic activity (magnitudes > 5) is 0.069 per year, the Richter b value is 0.8, and the maximum magnitude is 7.1 (These values are based on Ref. 5). Each magnitude M causes a rupture located at random on the fault of length $10^{(-3.31+0.708\ M)}$.

Service to the island of Alameda is provided by three links (see Figure 1). Risk of total or partial loss of water service to Alameda was calculated using the link resistances and peak ground velocity (PGV) attenuation equation of Reference 1. Four assumptions were used on ground motion: (a) deterministic estimates, (b) random and independent residuals at each node, (c) random and perfectly-correlated residuals, and (d) random but correlated residuals. For all cases of random ground motion, $\sigma_{\ln\ PGV} = 0.5$ was used. For the last case, which is the most realistic representation of ground motion, 30% of the total variance was given to the first three factors in equation (3) and 10% was given to the last.

Figure 2 illustrates the annual risk of failing one, two, or three pipelines to Alameda for the four representations of ground motion. Note that the ordinate on Figure 2 is annual probability of *occurrence*, not *exceedance*. It is clear that a deterministic representation of ground motion underestimates the risk; for this example, treatment of ground motion spatial correlation is also critical (for one or two failures); but this is not a general result. In terms of annual probability that one *or more* pipelines fail, the cases with random ground motion indicate a risk of about 0.025, and the deterministic case is 20% of this (i.e. it underestimates the risk by a factor of 5).

A second example, illustrated in Figure 3, is the calculation of total damage to a system of ten facilities (e.g. power plants) in Southern California worth $100 million each. For this application we use the faults and parameters of Ref. 5, the peak ground acceleration (PGA) equation of Ref. 6, and the following to estimate loss D (in %) as a function of PGA (in g):

$$D = 24.7 + 17.8 \log (PGA) \quad \text{for } PGA > .04g \tag{5}$$

Total damage to the system versus annual probability is shown in Figure 4. As for the previous example the treatment of ground motion uncertainty is important in calculating the risk of loss. Figure 5 shows the sensitivity to maximum magnitude by raising this parameter for the Sierra Madre fault (the dominant contributor) from 6.5 to 7.5, for two ground motion models (correlated and deterministic). Maximum magnitude has an important influence for the rarer events (larger losses) and is particularly important if a deterministic ground motion model is used.

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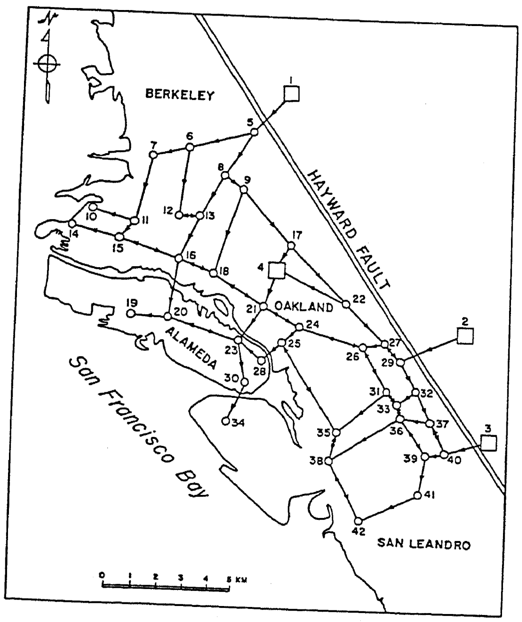

Figure 1: Water supply network in east San Francisco Bay (from Ref. 3)

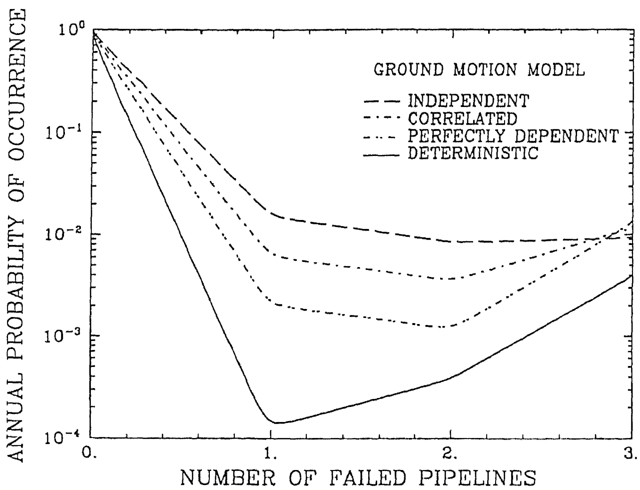

Figure 2: Risk of loss of service to Alameda.

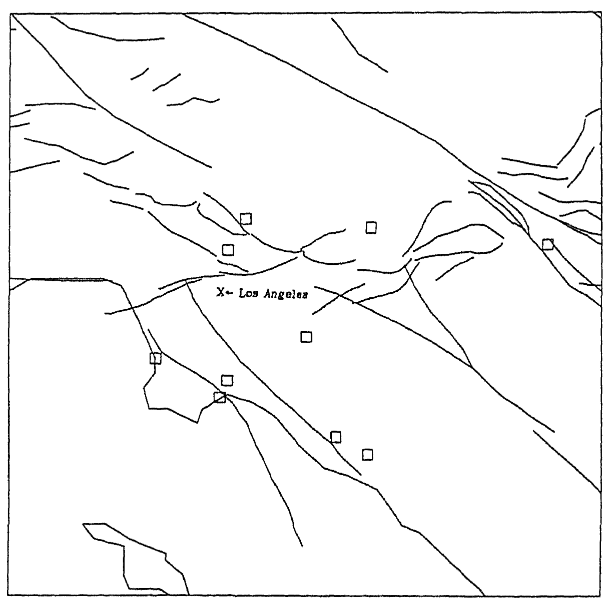

Figure 3: Ten facilities and faults in Los Angeles area.

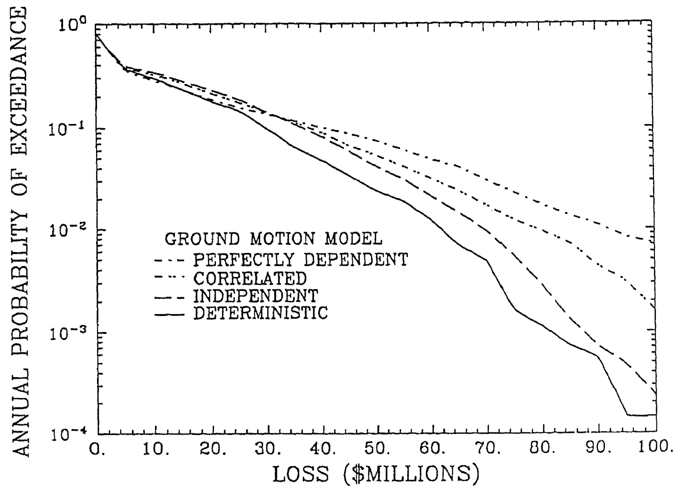

Figure 4: Risk of loss to ten facilities for different ground motion models.

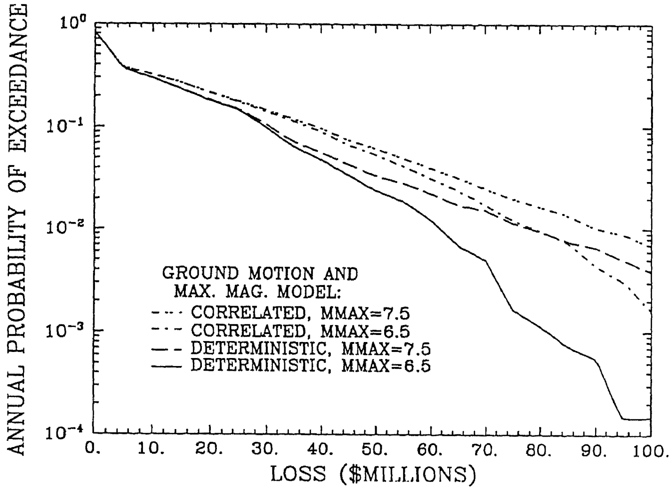

Figure 5: Risk of loss to ten facilities for different maximum magnitudes on Sierra Madre fault.