SEISMIC HAZARD AND SAFETY EVALUATION OF LIFELINE SYSTEMS

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SUMMARY

The failure of a lifeline system, consisting of a number of links, in an area of potential seismic activity, may be caused by the direct fault-rupture strike at one or more links in the system, or by the over-stressing of the links induced by high-intensity ground shaking. Either or both modes of seismic hazards may be important in evaluating the safety of a lifeline system. Methods for evaluating the seismic safety of a lifeline system against both types of hazards are developed. The methods are illustrated for the network of highways in the Boston area of Massachusetts.

INTRODUCTION

The safety or reliability of a lifeline system against earthquake hazards is one of the important factors that need to be considered in its design. The term "lifeline system," as used here, refers to networks of man-made or engineered systems (such as oil pipelines, water distribution systems, communication or transportation networks) consisting of several links and covering large surface areas.

A lifeline system may fail during an earthquake because of the fault-rupture striking one or more links of the lifeline system or the failure of the links caused by high intensity ground motions exceeding the resistance capacity of the links. In either case (i.e. modes of failure), because of randomness in the characteristics of future earthquakes, the estimation of seismic hazards may be expressed only in terms of probability.

Methods for the probabilistic analysis of both types of seismic hazards are presented herein. In either case, three types of seismic source models are developed; one or more of these source types may be necessary to model a region for seismic hazard analysis, ranging from regions with well-defined faults to those in which the fault system is completely unknown.

GENERAL ASSUMPTIONS

Tectonic earthquakes originate as ruptures along geologic faults. The length of the rupture zone is related to the total energy released, to the type of fault, and to other geological and regional factors; it may be several hundred kilometers long for a large-magnitude earthquake. Generally, the following equation is given to relate the rupture length, s, to the Richter magnitude, m.

$$s = e^{am-b} \tag{1}$$

where a and b are constants.

The failure of a given lifeline system obviously will depend on the failure of the individual links in the system. Whether or not a given link will be subject to a fault-rupture strike during the lifetime of the system can only be given in terms of probability and depends on several factors including the following:

(i) The location of the earthquake, as well as the frequency of earthquake occurrences in a region;

(ii) The position of the faults relative to that of a given link, and the direction of rupture propagation during an earthquake.

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The future occurrence of significant earthquakes in a region may be assumed to be a Poisson process; and the magnitude of an earthquake may be described with the shifted exponential distribution (Der Kiureghian and Ang, 1977), i.e.

$$f_M(m) = \frac{\beta \exp[-\beta(m-m_o)}{1-\exp[-\beta(m_u-m_o)} \qquad m_o \le m \le m_u \qquad (2)$$

$$= 0 \qquad \text{elsewhere}$$

where m_u is the largest possible earthquake in the region, m_o is the smallest earthquake that may be important in engineering, and β, the seismicity parameter, is the slope of the magnitude-recurrence curve for the region.

In light of Eqs. 1 and 2, the probability distribution for the rupture length, s, is,

$$f_S(s) = cs^{-(1+\beta/a)} \qquad s_o \le s \le s_u \qquad (3)$$

$$= 0 \qquad \text{elsewhere}$$

where $s_o = e^{am_o-b}$, $s_u = e^{am_u-b}$, and $c = \beta/[a(s_o^{-\beta/a}-s_u^{-\beta/a})]$.

During an earthquake of a given magnitude, the maximum intensity of ground shaking, y, will attenuate with increasing distance, r, from the zone of energy release. It is assumed that an attenuation equation in the form of $y = f(m,r)$ is available for the region.

PROBABILISTIC FORMULATION

Fault-Rupture Hazard

During an earthquake the fault-rupture may or may not strike one or more links of a lifeline system. This mode of failure is especially important in regions where earthquakes are of shallow foci and the ruptures are likely to intersect the ground surface.

Suppose that in a region, n potential earthquake sources were identified. Then, given an earthquake with its hypocenter located at i, see Figs. 1 through 3, the probability of a fault-rupture strike on a given link j is $P(L_j^i|E_i)$, in which L_j^i = a rupture strike on link j due to an earthquake in source i, and E_i is the event of an earthquake in source i. Thus the probability of a fault-rupture strike on link j due to an earthquake in source i is $P(L_j^i) = P(L_j^i|E_i)P(E_i)$. Considering n potential sources, the probability of a fault-rupture strike, i.e. $P(L_j)$ is

$$P(L_j) = P(L_j^1 \cup L_j^2 \cup \dots \cup L_j^n) = 1-P(\bar{L}_j^1\, \bar{L}_j^2 \dots \bar{L}_j^n) \qquad (4)$$

where $\bar{L}_j^i$ is the complementary event of L_j^i. For small probabilities $P(L_j^i|E_i)$ and $P(E_i)$, and assuming that L_j^i are statistically indpendent, it can be shown (Mohammadi, 1980) that

$$P(L_j) \simeq \sum_{i=1}^{n} P(L_j|E_i)\, P(E_i) \qquad (5)$$

where the superscript i is dropped for simplicity. Assuming uniform seismicity in the region

$$P(E_i) = \nu_i/\nu \qquad (6)$$

where ν_i and ν are, respectively, the occurrence rates in sources i and in the entire region. If the future occurrence of earthquakes is assumed to be a Poisson process with an activity rate ν, it can be shown that the annual probability of fault-rupture strike on link j becomes (Mohammadi, 1980),

$$P(L_j)_{\text{one year}} = 1-\exp[-\sum_{i=1}^{n} P(L_j|E_i)\nu_i] \tag{7}$$

Therefore, in evaluating Eq. 7, the main task involves the determination of the conditional probability $P(L_j|E_i)$. This will depend on which of the three types of sources, as modeled and described below, is appropriate.

Type 1 Source -- This source model assumes that the exact location and length of a fault are known, and will be appropriate if the potential seismic activity in a region is expected from a well-defined fault.

In this case, the required conditional probability in Eq. 7 is

$$P(L_j|E_i) = \int_{\ell} P(L_j|E_{i,s})\, f_S(s)\, ds \tag{8}$$

where $E_{i,s}$ is an earthquake in source i with rupture lengh s, and ℓ is the fault length. As shown in Fig. 1, if D_1 and D_2 are, respectively, distances from the intersection point of a link j with the fault to the nearest and farthest ends of the fault, it can be shown that for $D_2 \leq \ell$,

$$P(L_j|E_{i,s}) = \begin{cases} s/\ell & ;\ \text{if } \frac{s}{2} < D_1 < D_2 \\ (s/2 + D_1)/\ell; & \text{if } D_1 < \frac{s}{2} < D_2 \\ 0 & ;\ \text{otherwise} \end{cases} \tag{9a}$$

$$P(L_j|E_i) = \frac{c}{2\ell(1-\beta/a)}[(2D_1)^{1-\beta/a}+s_2^{1-\beta/a}-2s_o^{1-\beta/a}] - \frac{CD_1a}{\ell\beta}[s_2^{-\beta/a}-(2D_1)^{-\beta/a}] \tag{10a}$$

Similarly if $D_2 > \ell$,

$$P(L_j|E_{i,s}) = \begin{cases} (\frac{s}{2} - D_1)/\ell & ;\ \text{if } D_1 < \frac{s}{2} < D_2 \\ 0 & ;\ \text{otherwise} \end{cases} \tag{9b}$$

$$P(1_j|E_i) = \frac{c}{2\ell(1-\beta/a)}[s_2^{1-\beta/a}-(2D_1)^{1-\beta/a}] + \frac{cD_1a}{\ell\beta}[s_2^{-\beta/a}-(2D_1)^{-\beta/a}] \tag{10b}$$

where $s_2 = \min(2D_2, s_u)$.

Type 2 Source -- In this model, the exact locations of the faults in a region are not well defined, but the dominant direction of the faults is known. In this case, reference to Fig. 2 will show that a fault-rupture strike will occur only if an earthquake of magnitude m occurs within the shaded area. For an earthquake of magnitude m occurring in a small area ΔA_i, with distance D from the link, the rupture will strike the link j only if $\frac{s}{2}$ is greater than D. Therefore

$$P(L_j|E_i) = P(\frac{s}{2} > D) = P(M > m_1) = 1 - F_M(m_1) \tag{11}$$

where $m_1 = (\ln 2D + b)/a$, and

$$F_M(m) = [1-\exp\{-\beta(m-m_o)\}]/[1-\exp\{-\beta(m_u-m_o)\}].$$

Type 3 Source -- Finally, the fault system may be unknown; i.e. the fault location and direction are not defined. In such a case, the rupture may be assumed to propagate in any direction with equal probability; i.e. uniformly distributed in $(0, 2\pi)$.

As shown in Fig. 3, for an earthquake of magnitude m originating in a small area ΔA_i, the possible positions of a fault-rupture will form a circular area with diameter s. The rupture will strike the link j when this circle intersects the link. It can be shown that the probability of this event is,

$$P(L_j|E_i) = \int_{m_1}^{m_u} P(L_j|E_{i,m})\, f_M(m)\, dm = \int_{m_1}^{m_u} \frac{\theta}{\pi}\, f_M(m)\, dm \qquad (12)$$

where $m_1 = \max(m_o, m_1')$ in which $m_1' = (\ln 2D + b)/a$, D is the closest distance between the link and ΔA_i, and $E_{i,m}$ is an earthquake in the small source ΔA_i with a magnitude m. The value of θ depends on the distance D and the length of the rupture as summarized in Table 1.

TABLE 1: Value of θ for Type 3 Source

Case	Governing Inequality	θ
1	$D > \frac{s}{2}$	0
2	$D'' > D' > \frac{s}{2}$	$2 \cos^{-1} \frac{2\|y\|}{s}$
3	$D'' > \frac{s}{2} > D'$	$\cos^{-1} \frac{2\|y\|}{s} + \tan^{-1} \frac{x}{\|y\|}$
4	$\frac{s}{2} > D'' > D'$	$\tan^{-1} \frac{\ell_j - x}{\|y\|} + \tan^{-1} \frac{x}{\|y\|}$

In Table 1, x and y are coordinates of A_i, ℓ_j is the length of the link j, and D' and D'' are, respectively, distances from A_i to the nearest and farthest ends of the link (See Fig. 3).

Hazard from Severe Ground Shaking

The maximum ground motion intensity may exceed the resistance capacity of one or more links in a lifeline system. If a common material and the same fabrication process are used in constructing a lifeline system, it is reasonable to assume that the resistances along a link are perfectly correlated, even though the correlation between any two links may be weak. On this basis, the location of potential failure along a link may be assumed to be at the point of maximum ground motion along the link. The probability of the maximum ground motion exceeding some specified intensity y_r at a point along a link is

$$P(Y > y_r) = \sum_{i=1}^{n} P(Y > y_r|E_i)\ P(E_i) \qquad (13)$$

where Y is the maximum intensity (from n potential sources) at a point along link j. Again, assuming a Poisson process for future earthquakes with activity rate ν, it can be shown that

$$P(Y > y_r)_{\text{one year}} = 1-\exp[-\sum_{i=1}^{n} P(Y > y_r|E_i)\nu_i] \qquad (14)$$

The main problem, again, involves the determination of the conditional probability $P(Y > y_r|E_i)$ which can be evaluated as

$$P(Y > y_r|E_i) = \int_{m_o}^{m_u} P(Y > y_r|E_{i,m}) \ f_M(m)\ dm \qquad (15)$$

Eq. 15 must be evaluated for all potential sources in the region. Again three types of source models are necessary to permit the modeling of all conceivable seismic sources. These have been developed by DerKiureghian and Ang (1977), and may be used to evaluate the hazard from severe ground shaking. The results of such an analysis would be in the form of Fig. 4.

The safety of a lifeline system in this case depends on the consideration of the critical section of each link, where the probability of exceedance is the highest. The location of the critical section along a link may be determined by inspection; suggestions for this purpose are offered in Mohammadi (1980).

SAFETY EVALUATION OF A LIFELINE SYSTEM

The occurrence of a fault-rupture strike on a given link would be tantamount to the complete failure of the link, and thus the probability of a fault-rupture strike is also the probability of failure of the link. In the case of severe ground shaking the resistance of a link relative to the maximum motion-induced force or strain must be considered in evaluating its failure probability. As shown in Fig. 4, the annual probabilities of exceedance may be obtained as $1-F_Y(y_r)$; whereas the probability distribution of the resistance of a link may be described with the probability density function, f_R, of Fig. 5. The annual probability of a link failure due to severe ground shaking is, therefore,

$$P_{F_j} = \int_0^{\infty} [1-F_Y(y_r)] \cdot f_R(y_r)\ dy_r \qquad (16)$$

In either mode of failure, the failure probabilities of the individual links provide the information necessary to evaluate the failure probability of a complete lifeline system. For this purpose, a lifeline system may be modeled topologically as a network of parallel "paths" (Shinozuka, et al., 1978) each composed of several links in series. Some of the paths may have links in common and therefore may be partially correlated. Such correlations between the paths must be considered in the evaluation of the failure probability of the entire system. In order to include the effects of such correlations, the method of PNET (Ang, et al., 1975) may be used.

NUMERICAL ILLUSTRATION

For illustration, the seismic safety of the highway network around the Boston area in Massachusetts is considered (see Fig. 6). The hazards of fault-rupture strike and severe ground shaking are considered. The latter case is also discussed in Taleb-Agha (1977) for a resistance capacity of 75 cm/sec^2 (0.076 g) and for traffic flow from point 1 to point 5. The entire area is divided into 8 sources as given by the map of important earthquakes in the area (see Taleb-Agha, 1977). For the present analysis, the sources are all modeled as Type 3. The seismic parameter $\beta = 1.65$ and the attenuation equation $a = 1.183$ [exp(1.15 m]/r are proposed in Ref. 4 and were also used here. In the absence of information that may be more appropriate for the Boston area, the values $a = 1.576$ and $b = 7.560$ are used with Eq. 1.

The probabilities of the links to fault-rupture strikes and failure under severe ground motions for a mean resistance of 0.076 g are given in Table 2. The method of PNET (Ang, et al 1975) was used to consider the effects of correlations between different paths (Table 3), yielding the following result for the failure of the system. In the case of fault-rupture strikes, the system failure between Stations 5 and 1 is

$$P_F(5\text{-to-}1) = 2.16 \times 10^{-7}$$

whereas the probability of failure of the entire network due to ground shaking is

$$P_F(5\text{-to-}1) = 2.9901 \times 10^{-4}.$$

For the latter mode of failure Taleb-Agha (1977) obtained $P_F = 1.853 \times 10^{-4}$.

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REFERENCES

1. Ang, A. H-S., Abdelnour, J., and Chaker, A.A., (1975) "Analysis of Activity Networks Under Uncertainty," Journal of Engineering Mech. Division, ASCE, Vol. 101, EM4, pp. 373-387.

2. Der Kiureghian, A. and Ang, A. H-S. (1977), "A Fault-Rupture Model for Seismic Risk Analysis," Bull. of the Seism. Soc. of Am., Vol. 67, No. 4, pp. 1173-1194.

3. Shinozuka, M., Takada, S., and Kawakami, H. (1978), "Risk Analysis of Underground Lifeline Systems," Proc. U.S.-Southeast Asia Symp. on Engineering for Natural Hazards Protection, Ed. by A. H-S. Ang, Urbana, IL, pp. 44-58.

4. Taleb-Agha, G. (1977), "Seismic Risk Analysis of Lifeline Networks," Bull. of the Seism. Soc. of Am. Vol. 67, No. 6, pp. 1625-1645.

5. Mohammadi, J. (1980), "A Method for the Analysis of Seismic Reliability of Lifeline Systems," Ph. D. Thesis, Dept of Civil Engineering, Univ. of Illinois at Urbana-Champaign.

TABLE 2 ANNUAL FAILURE PROBABILITY OF LINKS

Link	Fault-Rupture Strike	Ground Shaking for $\bar{y}_r$=0.076 g	Link	Fault-Rupture Strike	Ground Shaking for $\bar{y}_r$=0.076 g
1	0.000012	0.000678	12	0.000084	0.001961
2	0.000015	0.001226	13	0.000117	0.000315
3	0.000024	0.000660	14	0.000029	0.000531
4	0.000013	0.001226	15	0.000077	0.000994
5	0.000086	0.001572	16	0.000069	0.000995
6	0.000083	0.004469	17	0.000043	0.002226
7	0.000094	0.004469	18	0.000043	0.000678
8	0.000055	0.000465	19	0.000118	0.000680
9	0.000123	0.001252	20	0.000017	0.004469
10	0.000185	0.001957	21	0.000029	0.000405
11	0.000096	0.001957	22	0.000087	0.000405

TABLE 3 ANNUAL FAILURE PROBABILITY FOR EQUIVALENT PARALLEL PATHS

Path	No. of Links		Annual Failure Probability Rupture Strike	Annual Failure Probability Ground Shaking
1	12	15-21-13-11-10-9-8-7-20-18-2-5	0.00103	0.02094
2	12	15-21-13-10-9-16-17-19-18-20-6	0.00091	0.02024
3	10	15-22-14-9-8-7-29-18-2-5	0.00068	0.01598
4	9	15-21-13-11-10-9-5-7-6	0.00065	0.01581
5	10	15-22-14-9-16-17-19-18-29-6	0.00065	0.01538
6	9	3-4-2-19-17-16-8-7-6	0.00045	0.01519
7	6	3-4-2-18-20-6	0.00021	0.01428
8	7	1-19-17-16-8-7-6	0.00021	0.01275
9	11	15-21-13-11-10-9-16-17-19-2-5	0.00086	0.01187
10	4	1-18-20-6	0.00016	0.01185
11	7	15-22-14-9-8-7-6	0.00055	0.01095
12	9	15-22-14-9-16-17-19-2-5	0.00065	0.00701
13	3	1-2-5	0.00011	0.00490
14	3	3-4-5	0.00012	0.00350

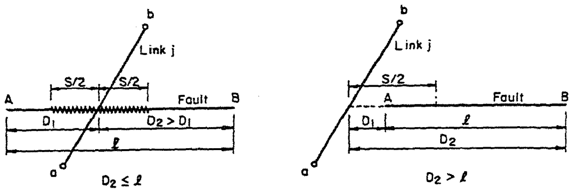

FIG. 1 TYPE 1 SOURCE

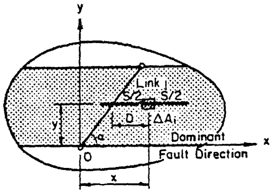

FIG. 2 TYPE 2 SOURCE

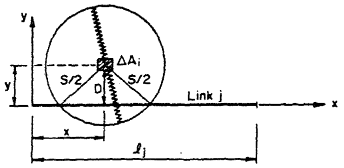

FIG. 3 TYPE 3 SOURCE

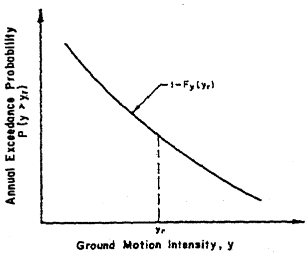

FIG. 4 ANNUAL PROBABILITY OF EXCEEDANCE

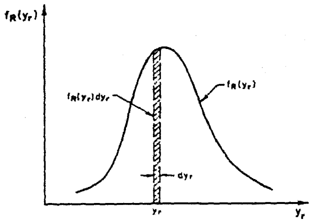

FIG. 5 PDF OF LINK RESISTANCE

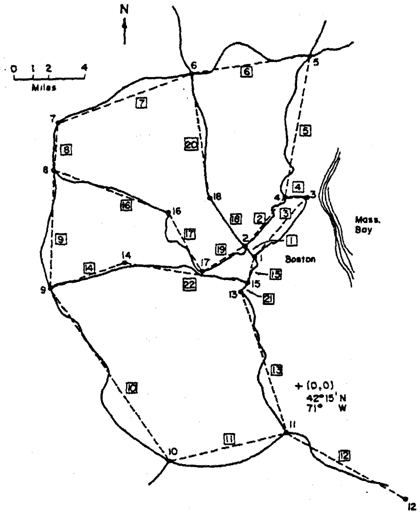

FIG. 6 MAJOR HIGHWAYS AROUND BOSTON