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ANALYSIS OF EARTHQUAKE RISK FOR LIFELINE SYSTEMS

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The use of maximum loss estimates and probabilistic loss estimates of losses from earthquakes is discussed. The two types of earthquake-related input required for risk analyses are noted. Two approaches to risk analysis are expressed mathematically. Risk analysis for lifeline systems is reviewed. Performance criteria for lifeline systems are suggested. Modelling of lifeline systems for risk analyses is covered. The analysis procedure used in the assessment of the state of a lifeline system following an earthquake is considered. This paper has emphasized the importance of asking the question: what is the probability that various fractions of a lifeline system may be knocked out by a single earthquake? The effect of geographical dispersion of key facilities upon the answer to this question has been illustrated by simple examples.

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PREFACE

This is a preprint of a paper to be presented at the EERI National Conference on Earthquake Engineering, to be held at the University of Michigan in June 1975.

ESTIMATES OF LOSSES FROM EARTHQUAKES

Estimates of the losses that might occur as the result of earthquakes are needed for a variety of purposes: setting rates for insurance premiums, planning for disaster relief, influencing the implementation of better building practices and planning investments in earthquake-mitigation research. In this context, losses potentially include both direct and indirect dollar losses, effects on people (such as deaths and injuries), and community impacts. However, most estimates usually deal with only the more tangible and quantifiable losses such as repairs costs, deaths and injuries.

In recent years, there have been a number of estimates of the losses that might occur during a major earthquake in California (for example, OEP 1972). A few such estimates have also been made for other parts of the country as well. These estimates are obtained by:

1. Assuming some particular epicentral location and magnitude for an earthquake; for example, a repetition of the 1906 San Francisco earthquake.
2. Estimating the resulting geographical distribution of the intensity of ground shaking.
3. Estimating the losses (deaths, injuries, repair costs, etc.) caused by the ground shaking, with consideration of the geographical distribution of population and value at risk.

No attempt is made to assess the probability that the presumed earthquake and resulting losses will actually occur. The use of such maximum loss estimates is a reasonable basis for planning and decision-making in California and other western states, where there is a very high probability that an earthquake of major proportions will strike a densely populated area within (say) the next half-century. However, such maximum loss estimates are less useful in the eastern and mid-western regions where the time intervals between the very large earthquakes may be several centuries or even tens or hundreds of centuries.

There have also been preliminary attempts at developing probabilistic loss estimates (for example, Liu and Neghabat, 1972; Whitman et al, 1975). In such analyses, a large number of different earthquakes (different magnitudes and different epicentral locations) are considered, with some probability of occurrence attached to each. Thus the more likely moderate earthquakes are considered as well as the less likely very large earthquakes, and the uncertainty in the location of future earthquakes is also recognized. The effects of all the various possible events are summed to provide a measure of the overall probability of earthquake-caused losses. This type of study is termed a risk analysis.

RISK ANALYSIS FOR A SPECIFIC SITE

Risk analyses, as applied to an individual building or facility or to a group of buildings (facilities) in a small area, require two types of earthquake-related input.

The first is an estimate of the probability that various levels of ground shaking will be exceeded at the location of interest. As indicated in Fig. 1, this estimate might be given by a curve relating annual probability of exceedence S to peak acceleration (or any other measure of the intensity of ground shaking). Such a curve might be developed purely from the historical record, or might be predicted by theoretical computations which combine together the historical record and geological information (Cornell, 1968; Algermissen, 1972).

The second required type of input is information concerning the earthquake losses as a function of the intensity of ground shaking. At any intensity, different facilities, even if designed for the same minimum level of earthquake resistance, will experience different degrees of damage as a result of variations in building practice and other factors. It hence is necessary to use some probabilistic representation of damage susceptibility.

One way to represent the losses is by a curve of expected loss L (repair costs, deaths, etc.) vs. ground shaking (see Fig. 1b). Then the expected annual losses EAL are obtained by:

$$EAL = \int L(A) \frac{dS}{dA} \quad dA \qquad (1)$$

This type of estimate of losses is useful only when one is prepared to take an average, long-term view; that is, to average significant losses occurring in a few years together with zero losses in most years, and to average losses over a number of buildings or facilities.

A second approach is to estimate the probability $P[F|A]$ that there is "failure." It is always difficult to define "failure," and the word can mean different things to different people at different times. For a building, "failure" might mean a dollar loss over some selected level, or it might mean there is a level of damage that significantly threatens life safety. From the standpoint of a city, "failure" might mean collapse of one or more buildings. However failure is defined, P[F|A] might typically have the form indicated in Fig. 1c. Then the overall annual probability of "failure" is given by:

$$P[F] = \int P[F|A] \frac{dS}{dA} \; dA \qquad (2)$$

This type of estimate is useful when the few very large losses (rather than the average of all losses) is of concern.

RISK ANALYSIS FOR LIFELINE SYSTEMS

Many lifeline systems (highways, water supply and distribution systems, etc.) are distributed over a considerable geographical area. Hence the seismic hazard parameter S may not be the same for all parts of the system, and the various parts will in general experience different intensities of ground shaking during any one earthquake.

If one wishes to determine the expected annual loss, then Eq. 1 may still be applied to each portion of the system, and the losses for the various portions may be summed to give the total expected annual loss.

However, a probability-of-failure approach may be more suitable for lifelines; after all, the very name "lifeline" suggests a system in which failure rather than just economic loss should be of concern. If this approach is applied to a lifeline system, then Eq. 2 must be modified as follows:

$$P[F] = \int\int P[F|\text{event}] \times P[\text{event}] \qquad (3)$$

where "event" means an earthquake of some magnitude and epicentral location, and the integration is over all possible magnitudes and locations. One event might be a local earthquake which causes very severe ground shaking over a small part of the system and moderate shaking over a larger part of the system, but only insignificant shaking over most of the system. Another event might be a very large but distant earthquake which causes moderate shaking over the entire system. In order to apply Eq. 3, the response of the system to each such event must be analyzed to determine whether or not the response is satisfactory or whether it constitutes "failure." In other words, the three steps outlined in the first paragraph are carried out repeatedly, with the outcome of each event weighted according to the probability of that event.

There are two main difficulties in the application of this approach: (a) the lack of general criteria regarding adequate performance of a lifeline system during an earthquake, and (b) the modelling of a complicated lifeline system.

PERFORMANCE CRITERIA

General risk-oriented design guidelines have evolved for buildings; e.g., the largest earthquake may cause damage but should not permit a collapse that might cause death. As yet, similar clearly stated guidelines have not emerged with regard to lifelines. It is essential that such guidelines be developed as soon as possible, even though they will inevitably be changed and refined as time passes. Once stated, guidelines imply the meaning of "failure" of a lifeline.

One general concept adapted from design of buildings may also apply to lifelines: during the largest earthquake there may be damage but there should be no failure that will endanger lives. This principle applies to water storage structures in developed areas, to large bridges and perhaps to gas pipelines. (There still is the problem of what is meant by the "largest earthquake," especially in the less seismic portions of the country.) As with buildings, use of this principle will imply some small risk of death, and it will be important to recognize and gain general acceptance for this level of risk.

However, it is easy to envision many "failures" of lifelines that will cause great human suffering and economic loss even though the direct risk of death is very small. Perhaps the best example is loss of water for fighting fires and the attendant possibility that a rapidly spreading fire might develop. Other examples are: interruption of local traffic networks required for rescue and relief; blockage of major transportation facilities required for bringing in supplies; loss of drinking water and attendant sanitation problems; etc. It probably is not feasible to design lifeline systems as to prevent all such "failures" anywhere in a system, and guidelines are needed to indicate acceptable levels of failure.

Table 1 (Whitman, 1974) is an attempt to suggest, mainly for the sake of argument, a possible set of guidelines. Several words of explanation are necessary.

* It is difficult to provide a simple definition of "major" and "moderate" earthquakes, precisely because a lifeline system extends over a large area. At this stage it is not clear which type of earthquake might be more damaging to lifelines; a very large earthquake at moderate distance which might have a moderate effect on a large part of the system, or a moderate earthquake with a very intense effect upon a small part of the system.

* It seems impractical to prevent all loss of service during a major earthquake, and even during a moderate earthquake. This leads to the concept of acceptable loss of service. The service lost during a major earthquake might be restored in several stages, with minimal necessary service restored quickly and full service over several months. As easterners, the writers might liken the acceptable loss of service during a moderate earthquake to that which occurs during a bad ice storm.

Undoubtedly all or part of these criteria are unobtainable; as stated before, they are presented primarily to stimulate discussion on this important general question.

MODELLING OF LIFELINE SYSTEMS

In general a lifeline system is a very complicated, interconnected network, as suggested in Fig. 2a. It is of course feasible to model an entire network, but for most risk analyses some considerable simplification will be necessary. The way in which these simplifications should be made depends very much upon the type of criteria used to judge the adequacy of network performance.

It appears useful to think of three types of simplifications: (a) treat key facilities as point "targets" without worrying about details of connectivity, (b) approximate main features of network by simple coarse networks, and (c) treat fine networks as area "targets."

Key facilities: Many systems will involve a relatively small number of facilities which are especially important to the overall functioning of the system as a whole. Examples would be generating stations in electric power systems, major pumping stations in water supply systems, etc.

Generally a lifeline system can still function reasonably satisfactorily if only one of a number of key facilities is lost, especially if the facility is knocked out of service for only a limited period of time. For example, generating stations (or at least units in a station) are routinely shut down for maintenance. Thus, having a single key facility "fail" during an earthquake does not necessarily mean that the entire system would "fail." However, if several such key facilities are lost unexpectedly and simultaneously (i.e., during the same earthquake), then the remaining key facilities might be unable to sustain operation of the overall system and there would be a system "failure."

Once key facilities have been identified, it is useful to perform a risk analysis to determine the annual probability that one facility will fail during some earthquake, that two targets will fail during the same earthquake, etc. Such estimates are of considerable use as input to decisions regarding the expenditure of funds to decrease system vulnerability to earthquakes.

Generally any lifeline system will contain a coarse, and in some instances reasonably simple, network of major arteries (highway system) or supply lines (high voltage lines for electrical system, major pipelines for water supply system).

Simple networks: With reasonably simple networks, it is feasible to analyze the state of the network following all possible earthquake events and to determine whether overall system performance criteria have been fulfilled.

The simplest case of a network is a series system (Fig. 2b). A typical performance requirement would be: it must be possible to pass from one end of the system to the other end. Then an earthquake-induced blockage at any point of the system would mean an overall system "failure."

Another simple case is a parallel system (Fig. 2c). If the performance criteria is being able to pass from one end to the other, then overall system "failure" occurs only if all branches become impassable. However, if the performance criteria has to do with capacity to transmit electricity or water or vehicles, then overall system failure would occur when some fraction of the total number of branches are blocked.

Fig. 2d shows a very simple form of cross-linked system. Here there are a number of possible performance criteria: being able to pass from A to C; being able to pass from A to both C and D; being able to pass from A to either C or D; being able to pass from either A or B to either C or D; etc. Panoussis (1974) has outlined how such problems may be decomposed into a series of problems involving simple series and/or parallel systems.

Fine networks: Most lifeline systems will involve, in some sense, a very fine network of elements. As examples, the total system for moving vehicles includes city streets as well as the main arteries, and a water supply system involves the street laterals in addition to the main supply lines. These fine networks typically are very redundant, and any analysis as a network for risk purposes is nearly out of the question.

For many purposes, the existence of the fine mesh may have relatively little effect upon the post-earthquake performance of the main arteries or supply lines. Thus, the system of city streets, which will tend to be quite clogged by debris and/or people following an earthquake, would be a very poor substitute for freeways from the standpoint of moving emergency vehicles. Similarly, the street laterals in a water distribution system would be ineffective, as substitutes for main trunk supply lines, in carrying water between distant parts of a metropolitan area.

Thus the performance of each square mile of fine mesh primarily affects the people in that square mile. From this standpoint, each square mile of fine mesh may be regarded as an individual "target," disconnected from all other such "targets." However, if too much of the fine mesh fails, then the ability of the overall system to accomplish the required repairs and restoration of service would be overtaxed. Thus, a possible measure of performance for the fine network portion of a lifeline system is the total geographical area in which extensive damage occurs.

ANALYSIS PROCEDURE

The problem of assessing the state of a lifeline system following an earthquake can, in most problems, be stated as: given a set of M "targets" distributed in space, find the probability that N of these M targets fail. These targets may represent key facilities, potential points of failure (bridges, hillside crossings, etc.) along the links of the coarse network of major arteries and supply lines, or the areas into which the fine mesh of the system has been divided. The resistance of each of the targets to failure may be different and will in general be uncertain.

Let us start with the simple case where all of the resistances are certain; that is, any one target fails if the ground shaking A exceeds the resistance R, but does not fail if $A \leq R$. The attenuation law giving the variation of ground shaking with distance D from an epicenter typically has the form:

$$A = b_1 e^{b_2 M} (D + d)^{-b_3} \tag{4}$$

where M is the magnitude of the earthquake and b_1, b_2, b_3 and d are constants. For a given epicentral location, a target will experience failure if

$$R^* = R(D + d)^{b_3} < b_1 e^{b_2 M} \tag{5}$$

The effective resistance R^* may be used to rank the failure susceptibility of each target for a particular epicentral location; thus, R_1^* is the smallest value of R^*, etc., giving the ranking $R_1^*, R_2^*, \ldots R_N^*, \ldots R_M^*$. Then, as the magnitude of the earthquake at that location increases, the target with R_1^* will fail first, etc.

The probability that at least one target fails, from an earthquake at a particular epicentral location, is then the probability of having at that location a magnitude M such that

$$b_1 e^{b_2 M} > R_1^* \tag{6}$$

The probability that at least N targets fail is the probability of an M such that

$$b_1 e^{b_2 M} > R_N^* \tag{7}$$

This process is repeated for all epicentral locations of interest, and the overall probability that at least N targets fail is the sum of the probabilities for the various locations.

A very efficient computer program, based upon the foregoing procedure, has been written and used for the examples given in the next section. The program permits use of any reasonable number of targets and different earthquake source areas. If the resistances of the several targets are uncertain, but a definite probability distribution can be assigned to each of the resistances, the same procedure may in principle still be used. However, the total number of cases to be examined may become excessively large. A program written in Russia by Keilis-Borok et al (1974) provides some of the desired capability.

EXAMPLES

A very simple problem involves two targets of equal, deterministic resistance lying within a very large uniform source area. (Panoussis [1974] analyzes the similar problem of two targets lying along a line parallel to a fault.) Fig. 3 gives a typical set of results for this problem, showing the annual probability of failure as a function of the spacing between the two targets. For the parameters used in this analysis, the annual probability of failure for one target alone is 4.9×10^{-3}.

The upper curve in Fig. 3 shows the probability that at least one of the two targets will fail. This curve would apply if failure of either target implied overall system failure. If the targets are immediately adjacent, both will receive the same shaking from any earthquake and hence either both will fail or both will survive. Hence the system failure probability is the same as the individual target failure probability. On the other hand, for very large spacing, the targets are independent and the overall system failure probability is twice the individual target failure probability. The curve shows that this condition is effectively achieved at a spacing of 100 to 120 km, although it is not exactly achieved until a spacing of about 165 km.

The lower curve shows the annual probability that both targets will fail in the same earthquake. This curve would apply if overall system failure occurs only when both targets fail. The overall system failure probability is exactly zero for spacings greater than about 165 km; for the parameters chosen, it then is impossible to have both targets fail during the same earthquake. A spacing about 92 km is required to reduce the overall system failure probability to 1/10 the individual target failure probability, and a spacing of about 127 km is needed for a reduction of 1/100. These spacings will of course be different for different values of the parameters involved in the analysis.

Fig. 4 shows a more complex example involving nine targets. The source parameters correspond to moderate to low seismicity, but the resistance of the targets (all the same) is also low. The computed probabilities that various numbers of targets fail is

No. sites failing	≥ 1	≥ 2	≥ 3	≥ 4	≥ 5	≥ 6
Annual probability	1.1×10^{-2}	3.0×10^{-3}	9.1×10^{-4}	1.7×10^{-4}	4.7×10^{-7}	0

SUMMARY

This paper has emphasized the importance of asking the question: what is the probability that various fractions (1%, 5%, 15%, etc.) of a lifeline system may be knocked out by a single earthquake? The effect of geographical dispersion of key facilities upon the answer to this question has been illustrated by simple examples.

ACKNOWLEDGEMENTS

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LIST OF SYMBOLS

A	level of ground shaking	P[F]	probability of failure
b_1 b_2 b_3	parameters	P[F|A]	probability of failure given ground shaking
D	distance	R	resistance
d	parameter	R*	effective resistance=$R(D + d)^{b_3}$
EAL	expected annual loss	r	number of earthquakes per year greater than M=4.3
L(A)	loss as a function of ground shaking	S(A)	annual probability that shaking A is equalled or exceeded
M	magnitude		
M_{max}	upper limit to magnitude	β	parameter in $\ln N(M)=\alpha-\beta M$ [N(M)= number of earthquakes ≥ M]

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Table 1

POSSIBLE GENERAL DESIGN GUIDELINES FOR LIFELINES

(for sake of discussion)

CATEGORY OF LIFELINE		MAJOR EARTHQUAKE	MODERATE EARTHQUAKE
		Intense ground motion or faulting in some part of system.	Moderate ground motion in some part of system.
WATER SUPPLY	Water storage reservoir	No failure that will endanger lives	No damage
	Local sources of water for fire-fighting	Adequate supplies remain available	Damage Level B
	Distribution systems	Damage Level A^1	
HIGHWAY SYSTEM	Bridges, overpasses	No collapses	No structural damage
	Roadways	Damage Level A	Damage Level B
ELECTRICAL SYSTEM		Damage Level A	Damage Level B
GAS SYSTEM		Damage Level A, but no contribution to fires	Damage Level B

Damage level A: No more than 20% of area without service; service fully restored within one month (within one week for damage level A^1).

Damage level B: No more than 1% of area without service; service fully restored within hours.

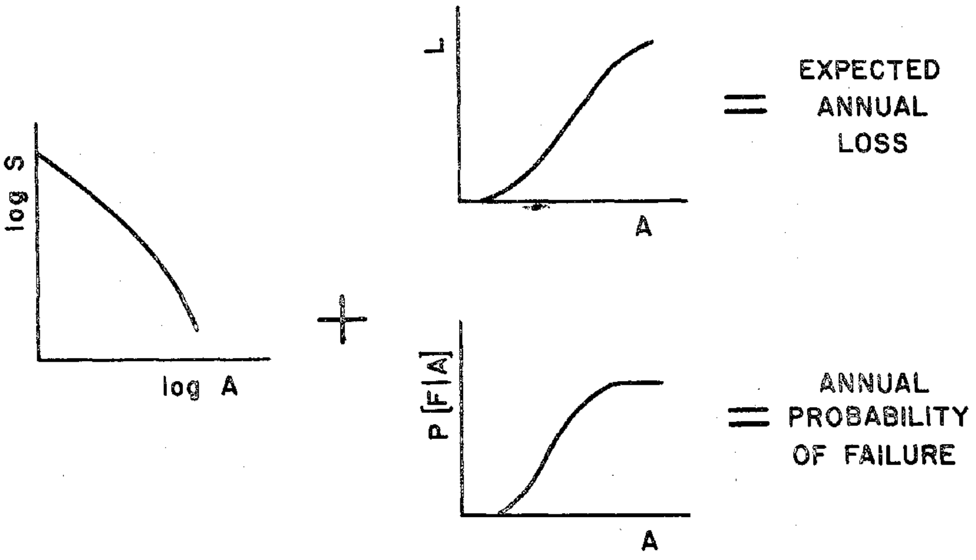


FIGURE 1. TWO STEPS IN SEISMIC RISK ANALYSIS: THE PROBABILITY OF GROUND SHAKING AND DAMAGE SUSCEPTIBILITY AS A FUNCTION OF GROUND SHAKING.

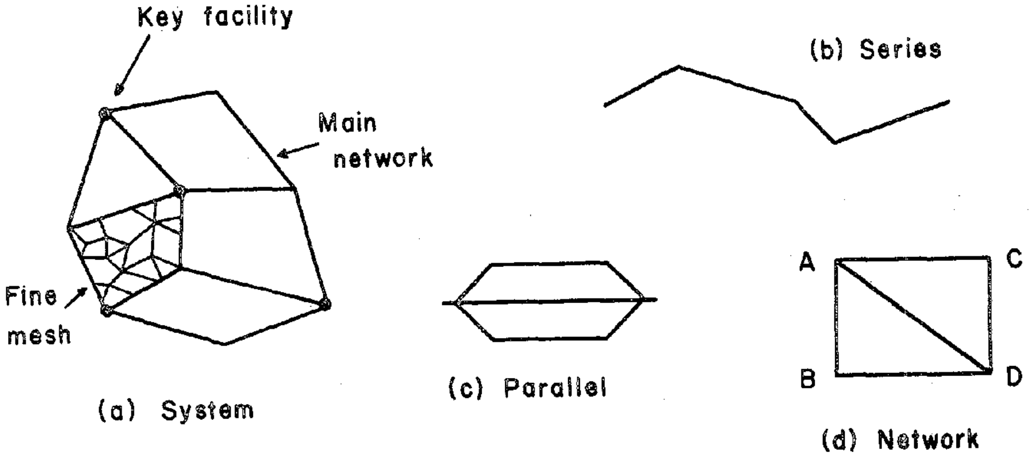


FIGURE 2. DECOMPOSITION OF SYSTEM (a) INTO KEY FACILITIES, MAIN NETWORKS (b through d) AND FINE MESH.

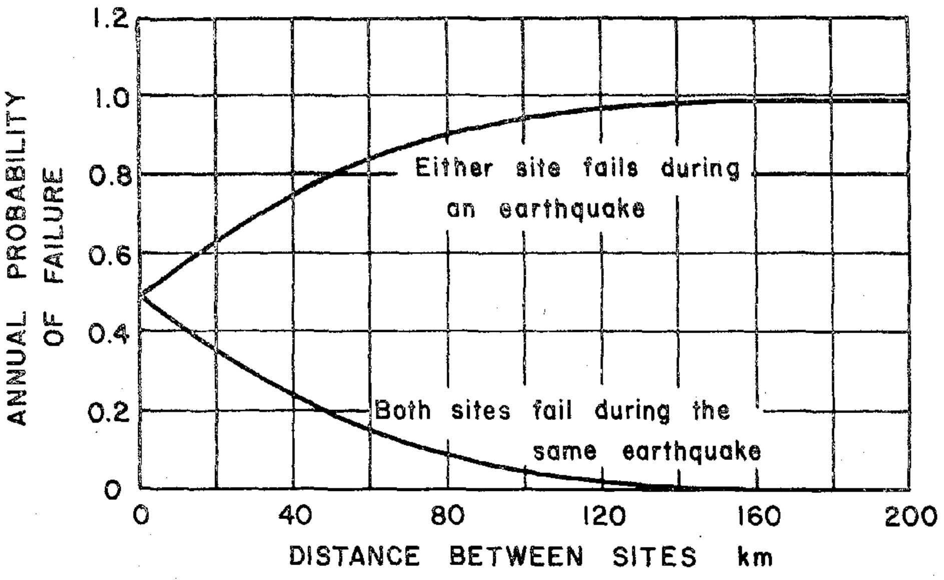
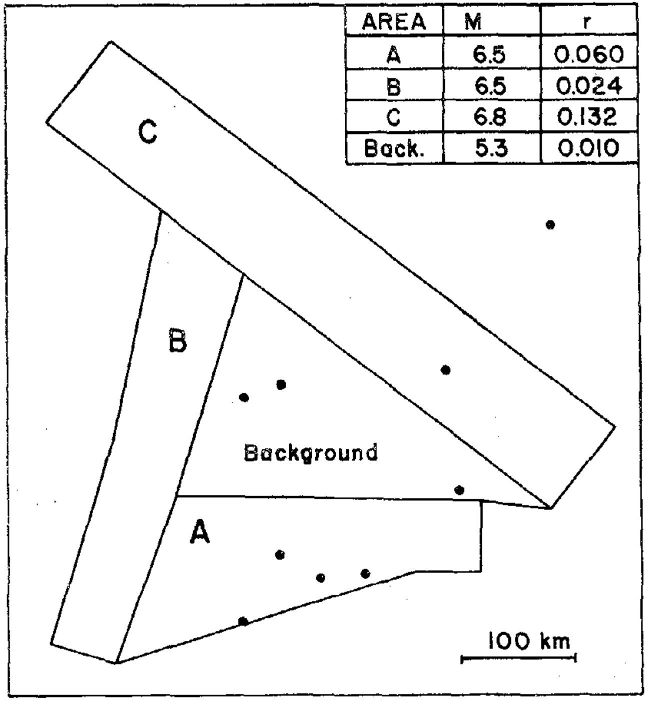


FIGURE 3. ANNUAL PROBABILITY THAT EITHER OR BOTH OF TWO SITES IN A UNIFORM SOURCE FAIL. CALCULATED ASSUMING R=100 cm/sec^2, β =1.1, M_{max}=7.7, r=7 x 10^{-6}/yr/km^3 AND ATTENUATION COEFFICIENTS FROM DONOVAN (1974)



AREA	M	r
A	6.5	0.060
B	6.5	0.024
C	6.8	0.132
Back.	5.3	0.010

FIGURE 4. MAP OF 9 SITES WITH SOURCE AREAS AND PARAMETERS. R=32 cm/sec AND β = 1.65.