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Determining Seismic Risk For Economic Optimum Slope Design

La détermination du risque sismique pour l'optimisation économique des plans d'une carrière

Die Bestimmung der seismische Gefahr für den Bau des ökonomisches Optimum im Tagebau

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ABSTRACT

Regional historical seismicity, regional tectonic processes, and data on local geologic structure are used to assess seismic risk for input into probabilistic slope design methods. Incorporation of earthquake risk into slope design makes economic optimization of open pit mine slopes possible in seismically active areas.

In designing open pit mines, the economics of slope design should reflect the trade-off between the benefits and increased risk associated with steeper slopes. The large number of landslides generated by earthquakes indicates that a slope designed to an acceptable level of risk under static loading conditions may prove to be unacceptable when dynamic loading is considered.

A Gumbel statistical analysis or similar probabilistic technique may be applied to the maximum yearly earthquake magnitudes occurring within seismically active zones near the site. The results of the Gumbel analysis are used to estimate earthquake risk within specified periods of time.

Intensity of ground motion at the site, given that an earthquake of a specified magnitude occurs within a given time period, is derived based on a study of local faulting and seismic attenuation laws. The resultant ground accelerations and their associated probabilities are then used in a Monte Carlo stability analysis to generate curves which approximate the risk of slope instability throughout the design "life" of the mine.

INTRODUCTION

Problem solving is often attempted in terms of absolutes; an alternative is either "safe" or "unsafe, a decision is "right" or "wrong." However, the way i which one arrives at such an absolute description of an alternative or decision is obscure at best. Since one can never know absolutely all of the parameters and facts which influence a project, it is more realistic to deal in terms of "risk" rather than "safety" in approaching complex engineering problems (Wiggins, 1973)[1]. An analysis based on the concept of risk permits a more efficient decision-making process and an opportunity to realistically balance conflicting objectives that might otherwise create economically disadvantageous overdesign or underdesign.

In assessing the economic feasibility of an open pit mine, for example, the conflicting objectives of steep slope angles, which create economic benefits du to reduction in waste stripping, should be balanced against the decreased risk of slope failure inherent in lower slope angles. This balance is accomplished in practice by selecting a "working slope" and modeling the mine for a specified period of time. This modeling allows the extraction of information relatin to annual ore and waste tonnages, average yearly grades, operating costs, and detailed pit geometry (Kim et al, 1976)[2].

Using a base of geotechnical data, probabilities o slope instability are calculated for each sector of the open pit during each operating period by determining potential failure modes and analyzing their stability (Call et al, 1976)[3]. The probability of instability is then incorporated into a benefit-cost analysis to determine an optimum slope angle.

Even though examples of seismically induced slope failures are numerous, seismic loads are seldom considered in studies of the economics of mining operations. This may largely be due to a common misconception that seismically induced landslides occur only in the immediate epicentral area of large earthquakes. This misconception has been reinforced by the Modified Mercalli Intensity Scale of 1931 in which the first description of induced landslides is associated with an Intensity of X (Wood and Neumann, 1931)[4]. The association of seismically induced landslides only with violent shaking underestimates the importance of dynamic loads since low levels of ground motion have triggered landslides at considerable distances from earthquake epicenters. Table 1 lists occurrences of seismically induced landslides in areas experiencing low levels of ground motion.

DETERMINATION OF EARTHQUAKE RISK

Numerous techniques have been used in earthquake engineering practice to generate design seismic parameters. The most common practice is to design structures to withstand shaking from a postulated "maximum" earthquake. The concept of a "maximum credible earthquake," "maximum expectable earthquake," "safe shutdown earthquake," "design basis earthquake," "operating basis earthquake," or "maximum probable earthquake," can be justified in civil engineering construction where the potential for life loss may be high. The "maximum earthquake," however, may actually have a very low probability of occurrence during the period of time for which a structure is designed. For this reason an analysis based on ground motions from a postulated "maximum earthquake" can lead to excessively conservative design for mining operations. An analysis to determine an economic optimum mine slope design should consider the probability of occurrence for different magnitude earthquakes, the maximum ground acceleration at the site from these earthquakes, the probability of experiencing a given acceleration at the site within a given period of years, and the predominant period of the accelerogram.

The probability distributions of maximum site acceleration and predominant period are calculated fro Gumbel extreme value statistics. This probability distribution is then sampled using a Monte Carlo technique in a benefit-cost model to determine if an earthquake acceleration occurs during a specified mining period. If the sampling indicates an earthquake acceleration at the mine, a dynamic slope stability analysis based on equations developed by Newmark (1965)[13] is then used to calculate a probability of slope instability schedule for that time period.

Extreme Value Technique

The theory of extremes developed by Gumbel (1958)[1] provides a convenient method for obtaining estimates of earthquake risk. This technique treats earthquake as a stochastic process F(x,t) where x is the variable of interest for design. For example, x may correspond to earthquake magnitudes recorded within a specific region, or to earthquake accelerations or intensity values at a particular site. Often the engineering design depends less on an accurate knowled of F(x,t) than on the largest value that x can assume within a given design period. If the entire earthquake catalogue [F(x,t)] is accurately known, then the maximum values of x are likewise known. However, the complete data needed for precise definition of F(x,t) are generally unavailable for most regions. Since the larger events are usually recorded, even i regions having poor instrumentation, the extreme valu technique, which uses these maximum values, provides a useful tool for such stochastic processes.

First, a time scale is divided into equally space intervals. Only the extreme value y which the variable x reaches within each interval is considered in the analysis. The extreme value y forms a regular point process within the original process F(x,t). Gumbel found only four mathematically distinct distributions of y. His "Type 1" distribution takes the form:

$$G(y) = \exp(-\alpha e^{-\beta y}) \qquad (1)$$

where α and β are found from a least squares fit (Lomnitz, 1974)[15].

When the parameters α and β have been determined, the probabilities of occurrence of an earthquake with a magnitude greater than the extreme value y are calculated from:

$$P(y) = 1 - \exp(-\alpha D e^{-\beta y}) \qquad (2)$$

where D is the number of years over which the probability is to be assessed.

The intensity distribution of ground motion at the site is estimated by applying representative attenuation relationships (Seed and Idriss, 1969[16]; Cornell, 1970[17]) either to (1) the magnitude distribution derived from the Gumbel analysis, or to (2) each individual earthquake in the earthquake catalogue and performing a Gumbel analysis on the resulting intensity distribution.

Examples of risk parameters useful in several open pit mine slope analyses performed recently include:

1) Exceedence Probability in One Year - The probability that a given magnitude y will be exceeded during any given year (Figure 1).

$$\text{Prob}\ (Y > y) = 1 - G(y)$$

2) Number of Shocks per Year - The yearly number of earthquakes above magnitude 0 is α. The expected number of shocks above an arbitrary magnitude M in a year is (Figure 2):

$$N_y = \alpha \exp(-\beta M)$$

3) Mean Return Period - If N is the expected number of earthquakes per year, T = 1/N is the mean return period in years (Figure 3).

4) Probability of Earthquake Occurrence - The probability of occurrence of an earthquake of magnitude greater than y in a D year period is (Figure 4):

$$P(y) = 1 - \exp(-\alpha D e^{-\beta y})$$

5) Probability of experiencing a given acceleration at the site within a given period of years (Figure 5).

Probabilistic Analysis Utilizing Entire Earthquake Catalogue - Maximum Likelihood Technique

Most probabilistic earthquake analyses that utiliz the entire earthquake catalogue partition the region surrounding the site into seismogenic zones (Algermissen and Perkins, 1970[18]; Cornell, 1970[17]). However instead of selecting only the maximum yearly magnitude all earthquakes within a zone are considered. Averag occurrence rates are calculated, then assigned to eac zone. These occurrence rates are assumed to be statistically independent for calculation of the probability distribution N_y (the number of earthquakes causing site motion with a given intensity y). Finally, the total probability at the mine site is calculated by summing the probabilities from each individual zone.

The earthquake risk analyses determine the probability of exceeding a given level of ground motion in a specified period of years at a mine site (Figure 5)

The maximum ground velocity, or acceleration, is the most frequently used measure for slope design. However, current work at the University of Arizona suggests the importance of the entire time-history of motion, particularly in the relationship of fatigue to dynamic slope failure.

Regardless of the probabilistic analysis preferred, thorough geological studies of regional and local faulting should be conducted. Remote sensing, geophysics, and surface and sub-surface mapping should be used to supplement the historical earthquake catalogue.

OPTIMUM SLOPE DESIGN

A benefit-cost analysis developed for CANMET as part of the recently completed pit slope design manual is used to evaluate the economic effects of slope instability on pit designs (Kim et al, 1976)[2]. In the benefit-cost package, Monte Carlo simulation is used to model the mining sequence of the pit. For the slope design the pit is divided into design sectors based on pit geometry, lithology, structure, rock and fracture strength properties, ore distribution, and operational considerations. Each design sector is evaluated during each mining period to acquire the costs of possible bench, interramp, and full slope instability. The occurrence of these instabilities is predicted by a probability of instability schedule for each sector (Table 2).

The probability of instability is developed from the stability analyses on potential failure modes in each pit sector. When earthquake probability is considered, a probability of instability schedule is determined for each earthquake acceleration in addition to a schedule for the non-seismic condition.

The earthquake probability of occurrence distribution is sampled during each mining period to determine if an earthquake has occurred. If so, a probability of instability schedule based on loading conditions corresponding to that earthquake motion is used. When an earthquake occurs, our analyses indicate that the probabilities of instability increase, resulting in a higher cost of instability during that mining period. The earthquake simulation is eventually applied to all pit sectors for that mining period.

A Monte Carlo simulation is also used to determine probability of instability. By sampling the distribution of the input geotechnical parameters a safety factor is determined from stability equations for the specific failure modes to be analyzed. Numerous iterations through the stability equation result in a distribution of safety factors. The logic used to determine the influence of earthquakes on stability is based on the application of the maximum acceleration associated with a given magnitude earthquake. If the slope withstands the expected maximum acceleration, the resulting safety factor is placed in the distribution of safety factors. If displacement occurs due to the application of the maximum acceleration, the shear strength is assumed to be immediately reduced by the displacement from an initial shear strength to a lower residual shear strength. This is a conservative assumption since the reduction of shear strength is actually a function of displacement

Using the post-displacement reduced shear strength a new safety factor is calculated without the earthquake load to determine the post-earthquake stability. If the slope fails under these reduced shear strength conditions, the resulting safety factor is less than 1 and is placed in the safety factor distribution.

If the post-earthquake slope shows stability, the earthquake causes displacement, but the slope has stabilized after the earthquake.

When post earthquake slopes are stable the displacement caused by the earthquake acceleration is considered in more detail based on an engineering estimate of earthquake displacement presented by Newmark (1965)[13]. He describes empirical relationships derived from laboratory displacement modeling. The approximate earthquake displacement is equal to the minimum of the following two functions:

$$\text{disp} = \frac{V^2 \cdot a}{2gN^2} \qquad (3)$$

$$\text{disp} = \frac{6\,V^2}{2\,gN} \qquad (4)$$

where V = maximum ground motion velocity during the earthquake

a = maximum earthquake acceleration in percent g

N = acceleration the slope can withstand in percent g

g = gravitational constant

If the earthquake displacement is less than a specified cutoff, the stable post-earthquake safety factor is added to the distribution. If the displacement exceeds the specified cutoff, the slope is considered to be at impending failure and a safety factor of 1 is added to the distribution.

The probability of instability is the number of safety factors less than 1 expressed as a percentage of the total number of iterations. If the safety factors are normally distributed, the probability of failure can be represented by the area under the normal curve that represents safety factors less than 1.

SUMMARY

In assessing the economic feasibility of an open pit mine the conflicting objectives presented by the economic benefits and increased risk of slope failur inherent in steep slope angles should be balanced. In areas of moderate to high seismicity the occurren of earthquake-generated dynamic loads may profoundly affect the economics of a mining operation. In assessing the risk due to seismic loads, probabilistic techniques such as Gumbel's theory of extremes, or maximum likelihood methods coupled with regional and local geological studies provide a convenient ar appropriate input into a probabilistic slope stability analysis. Realistic techniques for analyzing tl dynamic response of slopes are being perfected whicl should result in realistic economic optimization of open pit mine slopes in seismically active areas.

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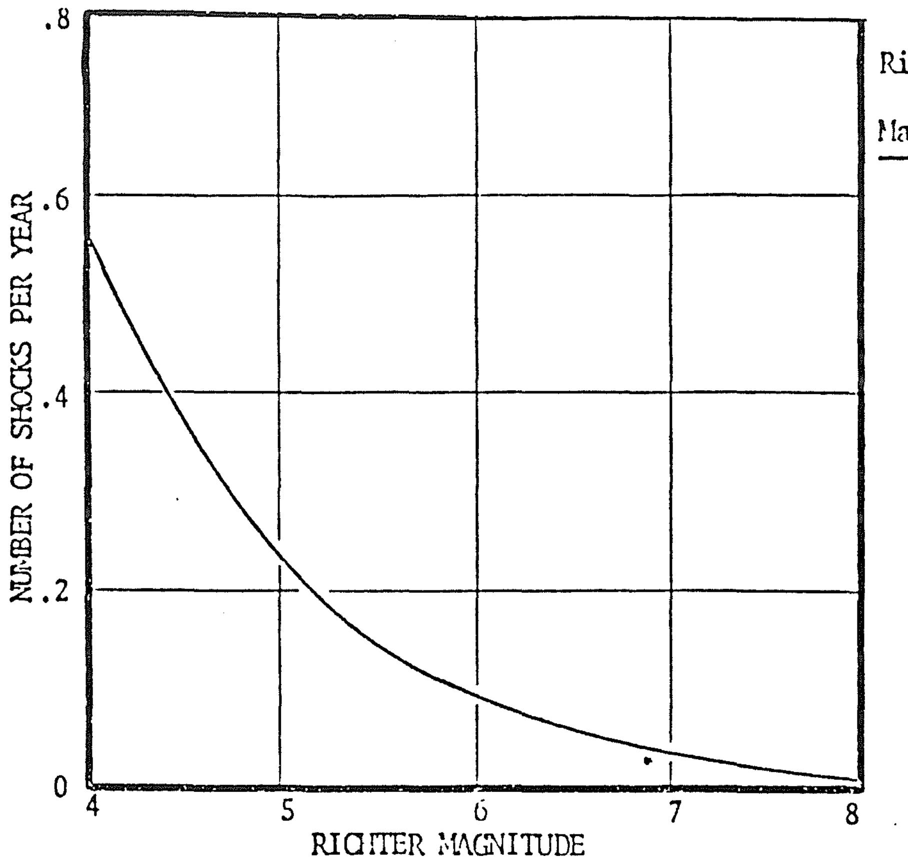
Table 1. List of Seismically Induced Landslides

Location	Date	Magnitude	Comments	Reference
Alaska	10 Sep 1899	8.6	Triggered avalanche 690 km from epicenter	(5)
Long Beach, Calif.	10 Mar 1933	6.3	Triggered landslide as far as 160 km from epicenter	(6)
Olympia, Wash.	13 Apr 1949	7.1	Landslides at distances up to 160 km away, in nearby mountains, large landslide near Tacoma	(6)
Hebgen Lake, Wyo.	17 Aug 1959	7.1	Large landslide 8 km from epicenter, 3 large landslides between 27 km and 35 km from epicenter, numerous rock falls 240 km from epicenter	(19)
Alaska	27 Mar 1964	8.3	Generated thousands of landslides throughout south central Alaska with radius 240 km from epicenter	
Hope, British Columbia	9 Jan 1965	3.1, 3.2	May have caused landslide of 130 x 10^6 metric tons	(7)
Peru	31 May 1970	7.8	Caused many rockfalls throughout Callejon de Huaylas region, ± 160 km from epicenter	(8)
San Fernando, Calif.	9 Feb 1971	6.6	Initiated or reactivated over 1000 landslides	(9)
Ferndale, Calif.	7 Jun 1975	5.2	Induced landslides in Rio Dell and Fortuna areas, 15 to 20 km from epicenter	(10)
Guatemala	4 Feb 1976	7.5	"Numerous landslides throughout central Guatemala." Extensive landsliding in Lake Attipau region, 200 km from epicenter and 100 km from end of fault rupture	(11)
Friuli, Italy	6 May 1976	6.5	Numerous landslides in the foothills region of Friuli	(12)

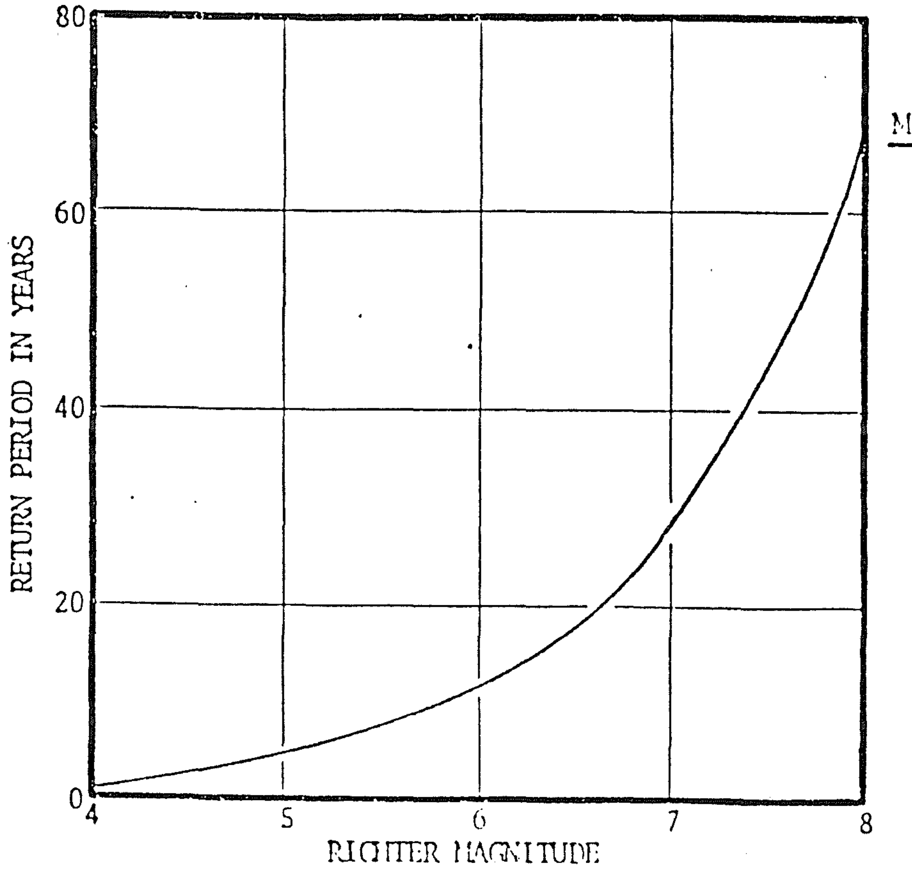
Table 2. Example Probability of Instability Schedule for a Pit Sector

Slope Angle (degrees)	Slope Height (meters) 10	25	45	90	180	340
10	.001	.001	.001	.001	.001	.001
32	.001	.003	.003	.004	.004	.006
38	.001	.003	.004	.009	.011	.015
43	.001	.204	.162	.173	.311	.499
58	.001	.447	.733	.950	.950	.950
64	.001	.609	.823	.950	.950	.950



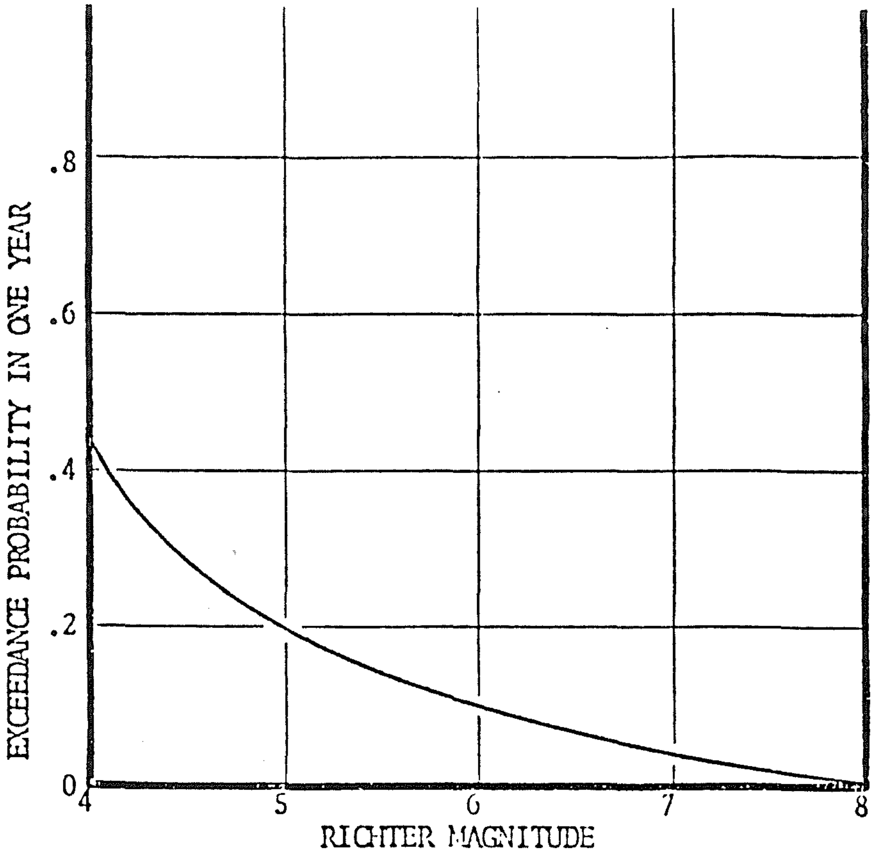
Richter Magnitude	Shocks Year
4	.59
5	.24
6	.11
7	.22
8	.01

Figure 2. Plot showing the number of earthquakes per year for a given Richter magnitude within 200 kilometers of the site.



Richter Magnitude	Return Period(yrs
4	1.6
5	6.2
6	11.2
7	30.0
8	69.1

Figure 3. Plot of earthquake return period for a given Richter magnitude earthquake within 200 kilometers of the site.



Richter Magnitude	Exceedanc Probabil
4	.45
5	.19
6	.10
7	.4
8	.10

Figure 1. Plot of the exceedance probability in one year for a given Richter magnitude earthquake within 200 kilometers of the site.

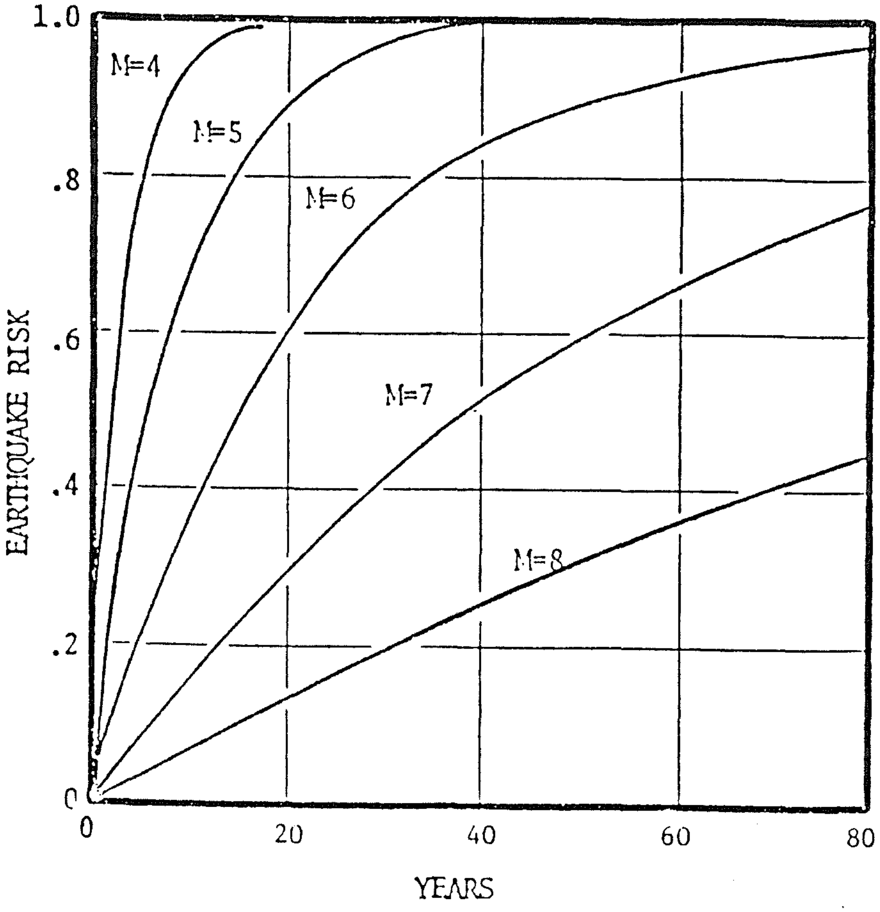


Figure 4. Plot of earthquake risk for a given time period within 200 km.

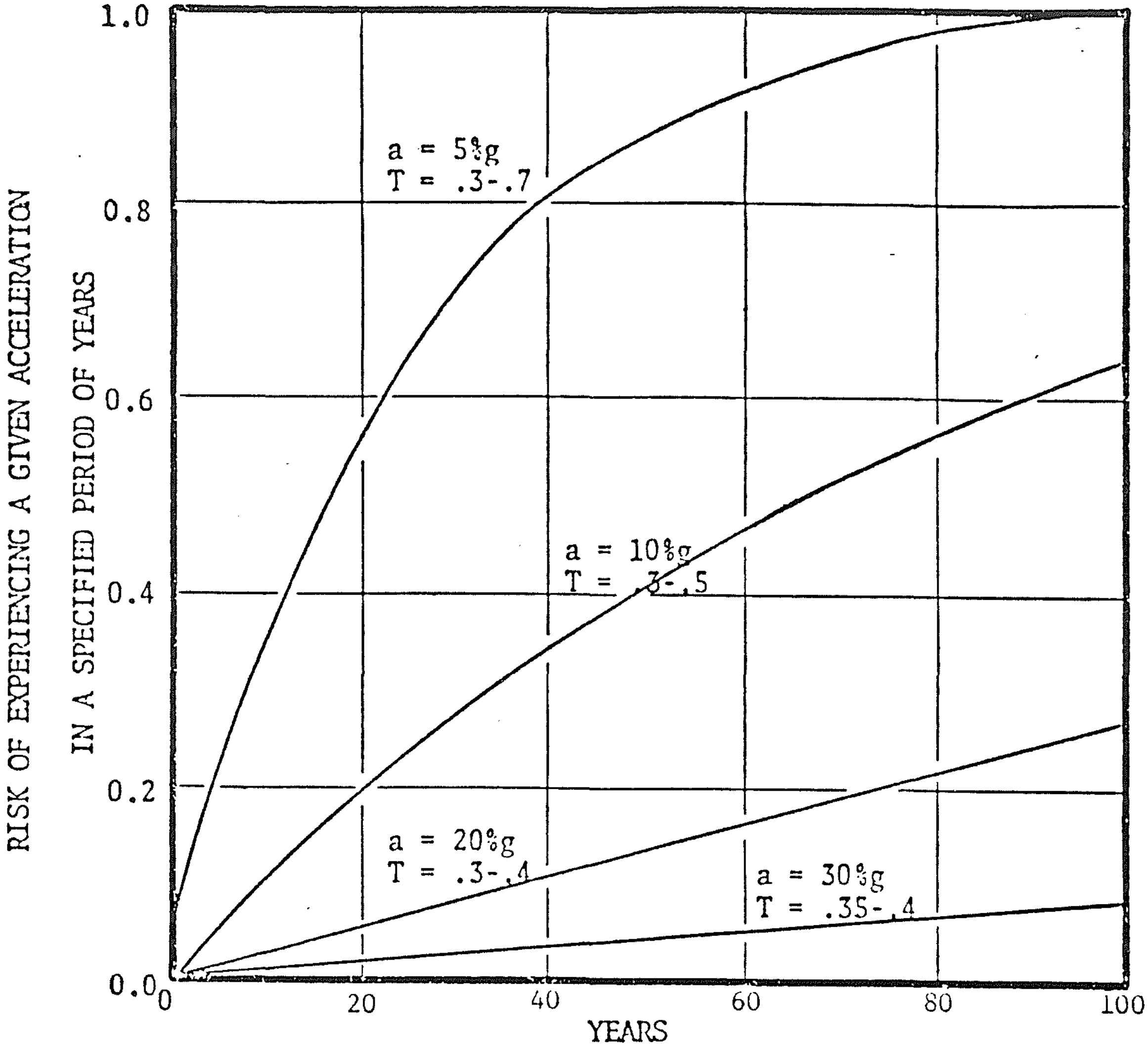


Figure 5. Plot of the risk of experiencing a given acceleration at the site within a given period of years, a = maximum ground acceleration, T = predominant period of accelerogram in seconds.