AN ENGINEERING ANALYSIS OF THE SEISMIC HISTORY OF NEW YORK STATE

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SUMMARY

The present study provides an engineering analysis of the seismic history of New York State. Data on ground motions which affected the State have been compiled and statistically analyzed. The resulting list contains 1289 seismic events that took place in the period between 1568 and 1975. A log-quadratic frequency-magnitude relationship appears to best represent the available data. The seismic risk that corresponds to the log-quadratic frequency-magnitude relationship is determined for a number of time periods and under the assumption that earthquakes occur in accordance with the Poisson model. The case where earthquakes follow a more general Markov process is also investigated.

INTRODUCTION

The possibility of an earthquake is an important design consideration in New York State. Nuclear power plants, large dams and other significant structures must be designed to successfully withstand ground shaking which, in some regions of the State (e.g., St. Lawrence and Buffalo-Attica regions), is of high intensity (Kulhawy, et al, 1977). The recorded seismic history of New York starts as early as 1568 when an earthquake of intensity between VII and VIII was felt strongly in the north and northeast regions of the State. The same regions were again affected in 1661 by another earthquake of the same intensity and with an epicenter in the St. Lawrence Valley of Canada. More recent seismic events of intensity VII or higher have taken place in the Clarendon-Linden Fault area (1929), in the Lake Erie area (1943) and in the area near Massena (1944). An earthquake of intensity between V and VI occurred in 1967 near Attica and was felt over an area of about 3000 square miles.

Various sources are used in this study to compile the data on ground motions that affected New York State. A detailed description of these sources can be found in Athanasiou-Grivas, et al (1978). In the case of seismic events for which only the Modified Mercalli Intensity (I) is reported, the following relationship is used to determine the Richter magnitude (m):

$$m = 1 + \frac{2}{3} I$$

Fig. 1 shows the histogram of the number of earthquakes for the examined 407 year period (1568-1975) of recorded seismic history of the State.

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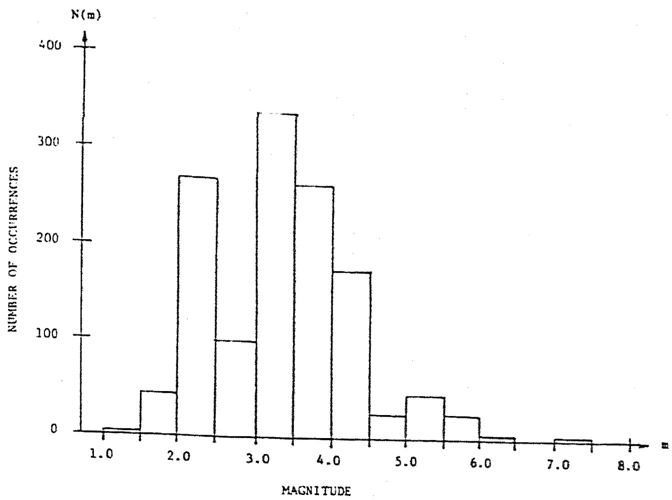

FIGURE 1. FREQUENCY OF EARTHQUAKES AS A FUNCTION OF MAGNITUDE (FOR THE 407-YEAR DATA BASE).

MAGNITUDE-RECURRENCE RELATION

On the basis of the available data, a relationship is developed between the Richter magnitude and the recurrence of earthquakes and for a range of the former between 2.0 and 7.0 (i.e., $2.0 \leq m \leq 7.0$). This range of magnitude involves 1242 seismic events. When the number of earthquakes N(m), with a magnitude greater than m, is divided by the base period, the average annual rate N'(m) is obtained. The following three functional relationships between N'(m) and m were studied:

$$\ell n\ N'(m) = A + Bm \quad (1a)$$
$$\ell n\ N'(m) = A + Bm + Cm^2 \quad (1b)$$
$$\ell n\ N'(m) = A + Bm + D/m \quad (1c)$$

The results are given in Table 1; these correspond to the data available for the last 50, 100, 150 and 200 years. The last column of Table 1 provides the error involved in each of the examined relationships. On the basis of the size of the error and the resulting shape of each of the three curves, it is concluded that the quadratic relationship, given by Eq. 1b, provides the best model for the available data. This is shown in Fig. 2 for the case of the entire 407-year period while similar curves can be obtained for other periods of interest (Athanasiou-Grivas, et al, 1978).

SEISMIC RISK ANALYSIS

Earthquake Occurrence Modeled as a Poisson Process

The seismic risk SR(m,t) is defined as the probability with which at least one earthquake with magnitude greater than m occurs during a time period t. Thus, if P_0 denotes the probability of no earthquake occurring

TABLE 1. COEFFICIENTS FOR THE "BEST FIT" MAGNITUDE - FREQUENCY RELATIONSHIP

PERIOD (YR)	A	B	C	D	ERROR
1925-1975	6.536 1.189 15.854	-1.557 1.426 -2.775	-.373	-15.758	2.907 .227 .622
1875-1975	6.259 .010 16.909	-1.565 1.922 -2.957	-.436	-18.011	4.440 .780 1.455
1925-1975	6.083 -.543 17.272	-1.579 2.119 -3.041	-.462	-18.923	5.159 1.044 1.865
1775-1975	5.328 .415 13.951	-1.410 1.332 -2.537	-.342	-14.582	2.665 .403 .709
1568-1975	4.827 1.600 11.122	-1.436 .203 -2.175	-.182	-11.519	2.927 1.150 .941

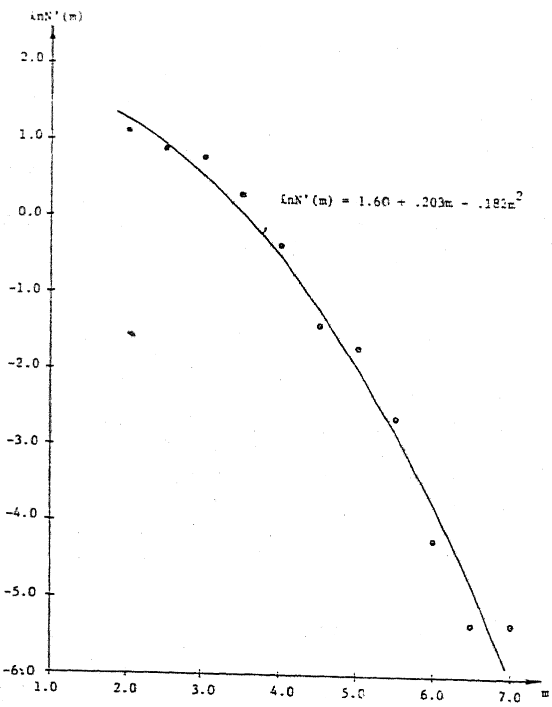

FIGURE 2. THE QUADRATIC "BEST FIT" RELATIONSHIP BETWEEN MAGNITUDE AND RECURRENCE OF EARTHQUAKES FOR THE 407-YEAR PERIOD.

with magnitude greater than m, then SR(m,t) is equal to

$$SR(m,t) = 1 - P_o \tag{2}$$

Furthermore, if it is assumed that the occurrence of earthquakes follows the Poisson model, the probability of the occurrence of k earthquakes with magnitude greater than m during the period t is equal to (Athanasiou-Grivas, 1978)

$$P_k = \frac{\exp[-N'(m)t][N'(m)t]^k}{k!} \tag{3}$$

where N'(m) is found from Eq. 1b to be equal to

$$N'(m) = \exp(A + Bm + Cm^2) \tag{4}$$

The probability P_o can be found by substituting a value for k equal to zero (k = 0) into Eq. 3; i.e.,

$$P_o = \exp[-N'(m)t] \tag{5}$$

Introducing the above expression for P_o into Eq. 2 and substituting N'(m) by the expression given in Eq. 4, one has

$$SR(m,t) = 1 - \exp[-t\exp(A+Bm+Cm^2)] \tag{6}$$

Figures 3 and 4 show the relationship between the seismic risk SR(m, t) and earthquake magnitude m for the time periods t = 1, 5, 25, 50 and 100 years. Figure 3 corresponds to the data available for the period of the last 50 years (1925-1975) and Figure 4 to those available for the last 200 years (1775-1975).

Earthquake Occurrence Modeled as Markov Process

The assumption that earthquakes follow a Poisson process implies that they are independent events that occur randomly in time. In order to account for the dependence that exists between subsequent seismic events, the use of the Markov process has been proposed as a model for earthquake occurrence (e.g., Vanmarcke, et al, 1973).

A sequence of events E_i, i = 1,2,...,n represents a Markov process if the following condition is satisfied:

$$P[E_n|E_1,E_2,\ldots,E_{n-1}] = P[E_n|E_{n-1}] \tag{7}$$

That is, the probability of the occurrence of the event E_n depends on the occurrence of E_{n-1} and is independent of all previous events. In this sense, a Markov process is said to contain a "one-step" memory.

The transition matrix of the Markov process can be written in the following form:

$$P(m) = \begin{array}{c} \\ 1 \\ 0 \end{array} \begin{array}{c} \begin{array}{cc} 1 & 0 \end{array} \\ \begin{bmatrix} p_{11}(m) & p_{10}(m) \\ p_{01}(m) & p_{00}(m) \end{bmatrix} \end{array} \tag{8}$$

where subscripts 1 and 0 denote the occurrence and non-occurrence, respectively, of an earthquake with magnitude greater than m. Thus, for example, $p_{10}(m)$ denotes the probability with which an earthquake with

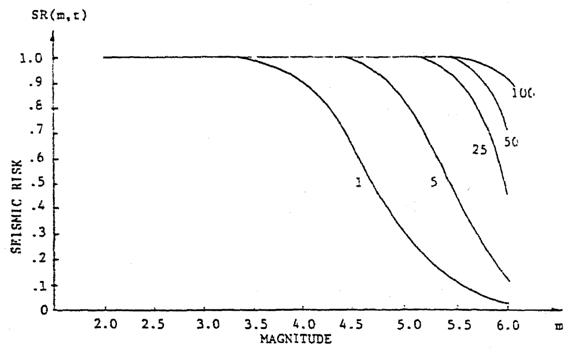

FIGURE 3. SEISMIC RISK vs MAGNITUDE FOR THE PERIOD 1925-1975 (50 years)

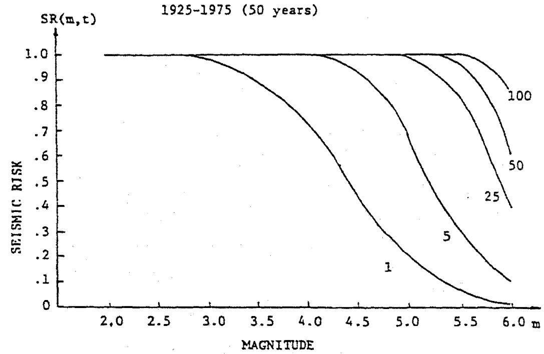

FIGURE 4. SEISMIC RISK vs MAGNITUDE FOR THE PERIOD 1775-1975 (200 years)

magnitude greater than m does not occur during a certain year given that such an earthquake occurred in the previous year.

As $p_{11}(m)$, $p_{10}(m)$ and $p_{01}(m)$, $p_{00}(m)$ represent probabilities of complementary events, respectively, one has

$$p_{11}(m) + p_{10}(m) = 1$$
$$p_{01}(m) + p_{00}(m) = 1 \qquad (9)$$

The probability of the occurrence of an earthquake with magnitude larger than m during the k-th year is equal to

$$\pi_k = \pi_o \; P(m)^k \qquad (10)$$

where π_o is the initial vector with elements the initial probabilities of occurrence and non-occurrence of this earthquake, and $P(m)^k$ is the transition matrix raised to the k-th power.

The seismic risk SR(m,t) for a period of t years is then equal to

$$SR(m,t) = 1 - (\pi_1)(\pi_2)\ldots(\pi_t) = 1 - \prod_{i=1}^{t}\pi_i \qquad (11)$$

i.e., SR(m,t) is the complement of the event "no occurrence of an earthquake with magnitude greater than m during the period t".

In Fig. 5 is shown the seismic risk of New York State for several time periods obtained by using a Markov process and the data available for the last one hundred years (1875-1975). Finally, in Fig. 6 is shown a comparison between the values of the seismic risk found by using a Poisson model and those found by assuming a Markov process on the data that correspond to the last 50 years (1925-1975). It can be seen that for small (t=1,5 years) and high (t=50,100 years) periods the assumption of a Poisson model yields higher values for the seismic risk.

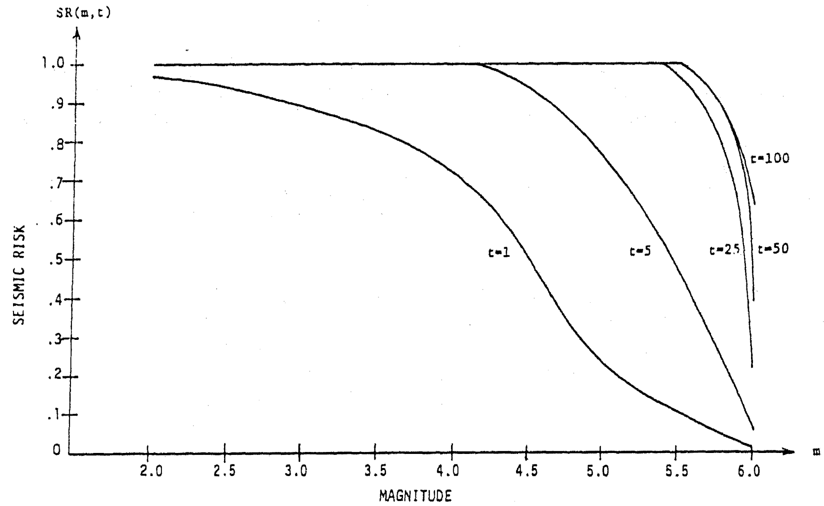

FIGURE 5. SEISMIC RISK FOR SEVERAL TIME PERIODS BASED ON DATA AVAILABLE FOR THE LAST 100 YEARS (1875-1975) - MARKOV PROCESS

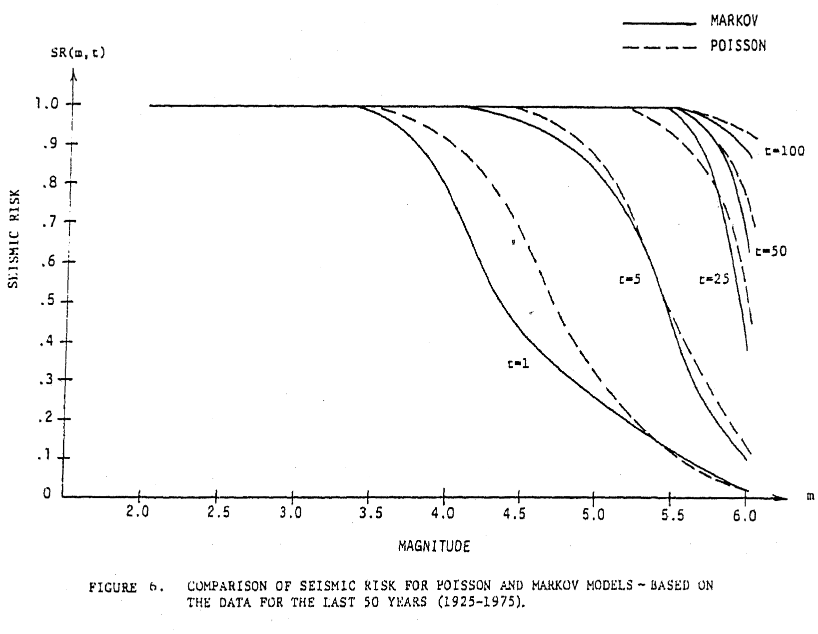

FIGURE 6. COMPARISON OF SEISMIC RISK FOR POISSON AND MARKOV MODELS - BASED ON THE DATA FOR THE LAST 50 YEARS (1925-1975).

ACKNOWLEDGEMENT

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