EARTHQUAKE OCCURRENCES IN WESTERN ANATOLIA BY MARKOV MODEL

Markov Modeli ile Batı Anadolu'da Deprem Oluşumları

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ABSTRACT

In this study, earthquake occurrences are evaluated by application of Markov model in the Western Anatolia with the 36° - 41° N latitude and 25° - 31° E longitude. The magnitude of M≥4.0 earthquakes are used between 1920-1995. Western Anatolia region is divided into 3 sub-regions with the ait of regional geology, seismotectonic properties, plate tectonic models and focal mechanism solutions.

6.0≤M≤6.4, 6.5≤M≤6.9 and M≥7.0 are defined as magnitude intervals. Transition probability matrices are obtained by transition probabilities of magnitude. Occurrence and non-occurrence probabilities of earthquakes are determined from transition matrices of magnitudes. From the results, when there is no earthquake in previous time interval, the occurrence of earthquake is low. In a similar way, if there is an earthquake in previous time interval, the probability of the non-occurrence of earthquake is high in the region for next time intervals.

ÖZET

Bu çalışmada 36° - 41° K enlemleri ve 25° - 31° D boylamları ile sınırlı Batı Anadolu bölgesinde, Markov modeli uygulanarak deprem oluşumları incelenmiştir. 1920-1995 yılları arasında magnitüdü M≥4.0 olan depremler kullanılmıştır. Bölgenin jeolojisi, sismotektonik özellikleri, plaka tektoniği modelleri ve odak mekanizma çözümlerinden yararlanılarak Batı Anadolu bölgesi üç bölgeye ayrılmıştır.

Magnitüd aralıkları 6.0≤M≤6.4, 6.5≤M≤6.9 ve M≥7.0 olarak tanımlanmıştır. Depremlerin olma ve olmama olasılıkları magnitüdlerin geçiş olasılık matrisleri ile elde edilmiştir. Sonuçlardan, bir önceki zaman aralığında deprem olmadığında deprem olma olasılığı düşük, aynı şekilde bir önceki zaman aralığında deprem olduğunda, gelecekteki zaman aralıklarında depremin olmama olasılığı yüksek olarak bulunmuştur.

INTRODUCTION

With the increasing amount of earthquake data becoming available, statistical models of earthquake occurrences have been gained greater importance. Statistical models allow one to reduce large data sets of earthquake occurrences to statistical parameters that describe these occurrences in a given region. They can be used to predict earthquake occurrences, maximum ground motions and earthquake hazard at a given region (Cornell, 1968).

Several statistical models have been proposed to represent the process of earthquake occurrence. The most common model is the Poisson model, which assumes spatial and temporal independence of all earthquakes including great earthquakes; i.e. the occurrence of one earthquake does not affect the likelihood of a similar earthquake at the same location in the next unit of time. Other models such as those proposed by Shlien and Toksöz (1970) and Esteva (1976) consider the clustering of earthquakes in time. A

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few other probabilistic models have been used to represent earthquake sequences as strain energy release mechanisms. Hagiwara (1975) has proposed a Markov model to describe an earthquake mechanism simulated by a belt-conveyer model. A Weibull distribution is assumed by Rikitake (1975) for the ultimate strain of the earth's crust to estimate the probability of earthquake occurrences. Knopoff and Kagan (1977) have used a stochastic branching process that considers a stationary rate of occurrence of main shocks and a distribution function for the space-time location of foreshocks and aftershocks.

Pınar et al. (1989) investigated seismic risk of the Aegean Region between the coordinates of 25°-31° East and 36°-41° North using the earthquake data for the years 1920-1986 according to the seasonal variations. They calculated seasonal earthquake future occurrence probabilities using Markov models. In accordance with the findings obtained through this method, they found that the earthquake risk probability was higher during seasons of spring and autumn. Altınok (1991) evaluated the seismic risk of West Anatolia by the application of Semi-Markov model. She used 75 earthquakes which have magnitudes 5.5 and higher in the time period of 1900-1986. She defined earthquake magnitude states as M1($5.5 \leq M \leq 6.0$), M2($6.0 \leq M \leq 6.5$) and M3($M \geq 6.5$). According to the interval transition probabilities of the magnitude-magnitude transitions, earthquakes with M1 magnitude was dominant in the region and the probability of occurring the other earthquake of M1 magnitude following the first one was high.

The objective of this study is to describe Markov model for characterising the occurrence of great earthquakes consistent with the general physical processes contributing to their occurrences.

SEISMICITY OF THE WESTERN ANATOLIA

Western Anatolia is one of the four major neotectonic provinces in Anatolia (Sengör et al., 1985). They pointed out that the province originated following the collision of Arabian and Anatolian land masses during the Middle Miocene. As a result of that collision, westerly escape of the Anatolian block introduced EW compression in Western Anatolia which began to be relieved by NS extension.

The seismicity in Western Anatolia is high and displays swarm-type activity with remarkable clustering of low-magnitude earthquakes in time and space (Üçer et al., 1985). Epicenters of earthquakes for the period 1920-1995 and magnitudes $M \geq 4.0$ for the Western Anatolia are shown in Figure 1. The data for this study were taken from various catalogs(1920-1970, 1970-1990, 1990-1995) prepared by Ayhan et al., Yatman et al., and Bağcı et al.). Fault-plane solutions reported by Alptekin (1973), Canıtez (1967), Kocaefe(1981) and McKenzie (1972, 1978) are shown in Figure 2. Focal mechanisms of earthquakes in Western Anatolia indicates that intra-plate deformations arising from vertical movements are occurring inside the Aegean-Turkish block. Similar deformations are probably occurring in the north Aegean and Greece. All fault-plane solutions in Western Anatolia represent normal faulting, indicative of crustal extension. Tensional axes for these solutions are nearly horizontal and perpendicular to the general east-west trend of graben structures.

DEVELOPMENT OF THE MODEL

The basic idea comes from the fact that according to the Elastic Rebound Theory there is a storage of strain energy that has to build up before a new event takes place. This means that the probability of the future event depends on the past history of earthquakes in such a way that

$$\mathrm{Prob}(n_k,t_k/n_0,t_0;n_1,t_1;....n_{k-1},t_{k-1})=\mathrm{Prob}(n_k,t_k/n_{k-1},t_{k-1}) \quad (1)$$

where n_i,t_i are respectively the number of events n_i to occur in the time interval t_i; or in other words the probability of being in a state k after considering all the states from zero up to k depends only on the probability of being in the state k-1. This is a first order Markov chain or a one state memory characterised by the transition probability, $\mathrm{Prob}(n_k,t_k/n_{k-1},t_{k-1})$

To define a Markov process, the probability of making the next transition to each other state given these conditions must be specified for each state in the process and for each transition time (Howard, 1971). Thus the quantity,

$$P_r=[n_{k-1}=j I n_k=i] \quad (2)$$

must be specified for all $1 \leq i$, $j \leq N$, and for n=0,1,2,....

The transition probability P_{ij} is defined as:

$$P_{ij}=P_r[n_{k-1}=j I n_k=i] \qquad 1 \leq i,\ j \leq N,\ k=0,1,2,.... \quad (3)$$

The transition probability P_{ij} is the probability that a process presently in state i will occupy state j after its next transition. Since each transition probability P_{ij} is a probability, it must satisfy the requirement,

$$0 \leq P_{ij} \leq 1 \qquad 1 \leq i,\ j \leq N \quad (4)$$

The possibility of the same state's being occupied after a transition- the probabilities P_{ij}, i=1,2,.......N are not necessarily zero since the process must occupy one of its N states after each transition,

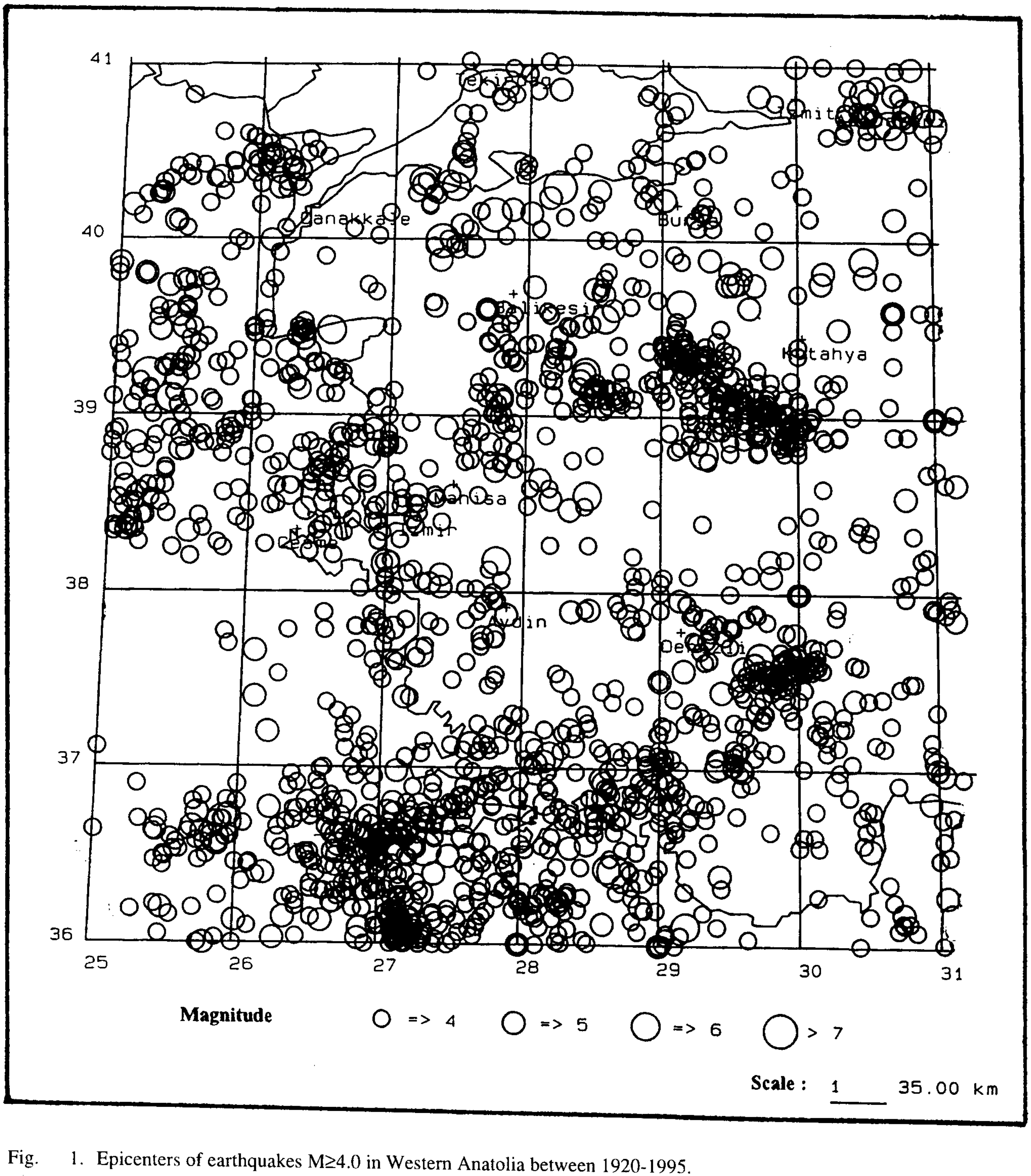

Fig. 1. Epicenters of earthquakes M≥4.0 in Western Anatolia between 1920-1995.

Şekil 1. Batı Anadolu'daki M≥4.0 olan depremlerin magnitüdlerine göre episantır haritası (1920-1995).

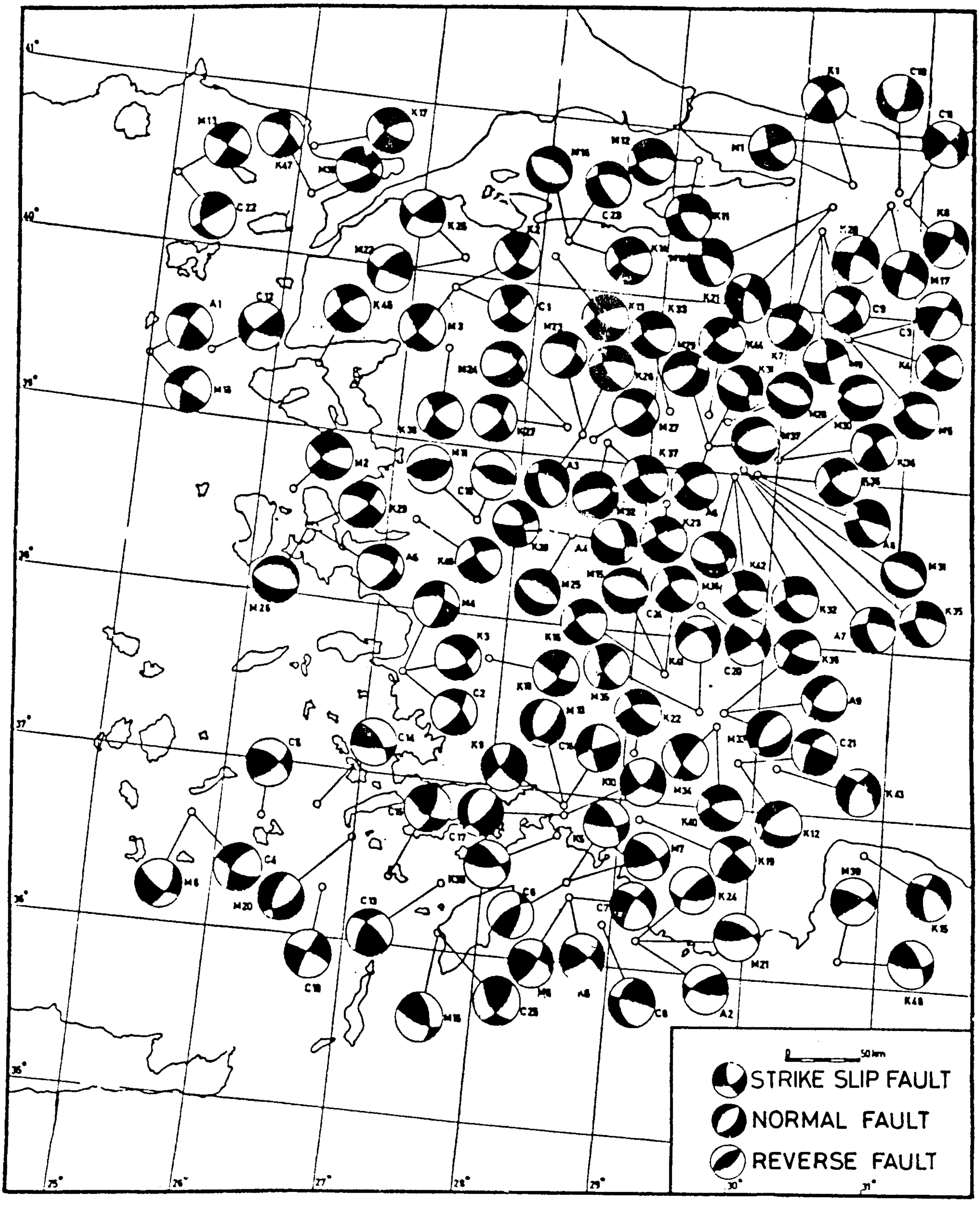

Fig. 2. Fault plane solutions.
Şekil 2. Fay düzlemi Çözümleri.

$$\sum_{j=1}^{N} P_{ij}=1 \qquad i=1,2,.....N \qquad (5)$$

The N^2 transition probabilities that describe a Markov process are conveniently represented by an N by N transition probability matrix P with elements P_{ij},

$$P=[P_{ij}]=\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1N} \\ P_{21} & P_{22} & \cdots & P_{2N} \\ \cdot & \cdot & \cdots & \cdot \\ P_{N1} & P_{N2} & \cdots & P_{NN} \end{bmatrix} \qquad (6)$$

The entries in P must satisfy the requirements imposed by Equations (4) and (5). A matrix whose elements can not lie outside the range (0,1) and whose rows sum to one is called a stochastic matrix; thus the transition probability matrix that defines a Markov process is a stochastic matrix. Because the rows of the transition probability matrix sum to one, only N(N-1) parameters are necessary to specify the probabilistic behaviour of an N-state Markov process.

Transition probability matrix of a Markov process, and hence the process itself, can be graphically represented by a transition diagram, similar to the one shown in Figure 3, formed of nodes and directed line segments called branches. Each node is numbered to represent one state of the process. A directed line segment or branch is drawn from each node i to each node j and labelled with the transition probability $_{ij}$. Markov model is applied to earthquake occurrences. Considering the events:

1. no earthquake occurs
2. an earthquake occurs

and according to the transition probability matrix is

$$P=\begin{bmatrix} 1-a & a \\ b & 1-b \end{bmatrix} \qquad (7)$$

where a and b represent probability of having one earthquake in this current period of time given that one earthquake occurred during the last period and probability of having one earthquake in this current period of time given that no earthquake occurred during the last period, respectively. The corresponding transition diagram appears in Figure 4. The period of time should be chosen such that not more than one earthquake occurs.

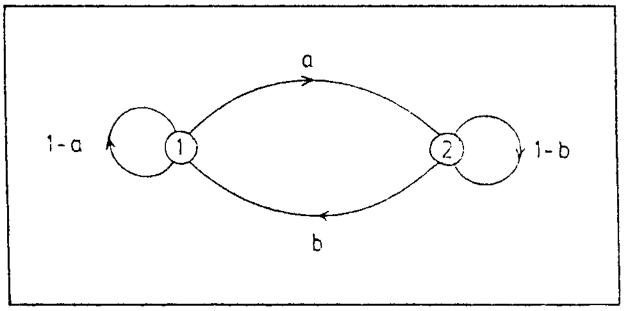

Fig. 3. Transition diagram between states.
Şekil 3. Durumlar arasındaki şematik geçiş diyagramı (Howard, 1971).

APPLICATION OF THE MODEL

The model described above can be applied to Western Anatolia subjected to great earthquakes. For the application of the model, Western Anatolia is divided into 3 sub-regions with the aid of regional geology, seismotectonic properties, plate tectonic models and focal mechanism solutions as shown in Figure 5. Since the primary object of this paper is to demonstrate the feasibility of applying the Markov model to the occurrence of great earthquakes and not to establish specific parameters for a selected sub-region, possible inaccuracies in the delineation of sub-regions are not significant. When occurrence parameters are to be established for a given sub-region, appropriate data should be evaluated carefully before the model is applied.

The procedure of calculating probabilities of different magnitude group earthquakes ($6.0 \leq M \leq 6.4$, $6.5 \leq M \leq 6.9$, $M \geq 7.0$) in a sub-region within a specific period of interest (1920-1995) using a Markov model consists of the following steps:

a. Define states (magnitude groups) and unit time for the Markov model.

b. Define the initial seismicity condition of the zone in terms of the magnitude of the last great earthquakes in the sub-region and the time elapsed since then.

c. Assess the model parameters consisting of the transition probabilities P_{ij} on the basis of available historical seismicity.

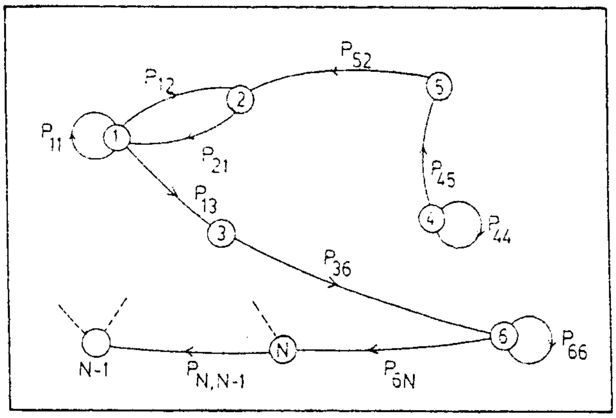

Fig. 4. Transition diagram for two-state Markov process.
Şekil 4. İki durumlu model içinşematik geçiş diyagramı. (Howard, 1971).

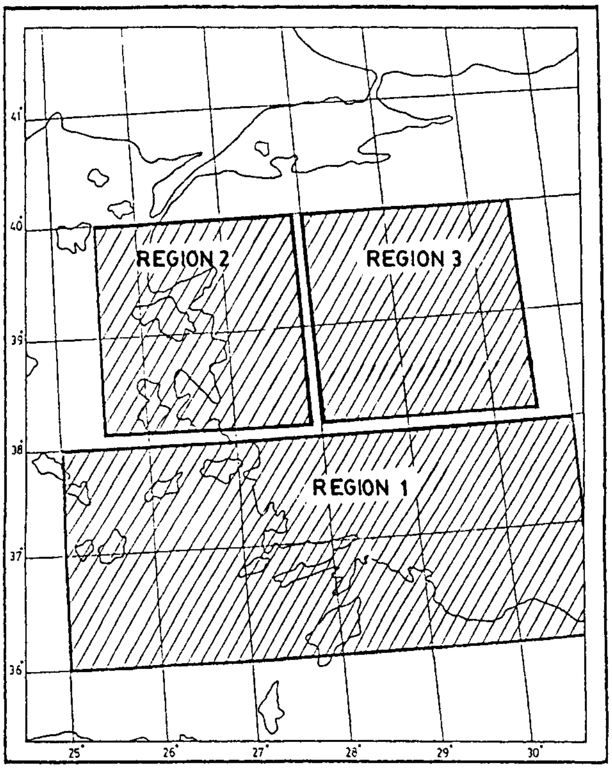

Fig. 5. Location map of studied regions.
Şekil 5. Çalışılan bölgelerin yerleşim haritası.

d. Use Equation (7) to calculate the transition probabilities of N earthquakes of different magnitude groups during the time period.

Three different magnitude groups (6.0≤6.4, 6.5≤M≤6.9 and M≥7.0) were defined for the occurrence of great earthquakes. A unit time for a Markov model should be small enough so that the probability of two or more transitions (great earthquakes) is very low and large enough so that only a limited number of transitions need to be studied during the selected period of interest. Based on these considerations, a unit time of 5 yr was selected. The initial conditions need to be defined for each zone, the size of the last great earthquake and the time elapsed since its occurrence. Both conditions can be established relative easy for zones which have had at least one great earthquake in historical times. In such cases, the known great earthquakes are arranged in a chronological sequence, and the last earthquake in the sequence is identified as great earthquake.

DISCUSSION AND CONCLUSIONS

The primary result obtained from the model is the set of probabilities of occurrences of different magnitude earthquakes in a given region during a specified period of interest. Selected magnitude groups (6.0≤M≤6.4, 6.5≤M≤6.9 and M≥7.0) are used to obtain the transition probabilities after specified period(1995) with 5 years unit time intervals. Table 1, 2 and 3 show the occurrence and non-occurrence probabilities of earthquakes which are grouped in 6.0≤M≤6.4 for the regions 1, 2 and 3. The probabilities of occurrences of same earthquake magnitude group during the next 30 years after 1995 are shown in Figures 6, 7 and 8. From these figures, in the case of the ab-

Table 1. The occurrence and nonoccurrence probabilities of earthquakes 6.0≤M≤6.4 (Region 1).
Çizelge 1. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (1. Bölge).

n	P_{11}	P_{12}	P_{21}	P_{22}
0	0.5600	0.4400	0.6700	0.3300
1	0.6084	0.3916	0.5963	0.4037
2	0.6031	0.3969	0.6044	0.3956
3	0.6037	0.3963	0.6035	0.3965
4	0.6036	0.3964	0.6036	0.3964
5	0.6036	0.3964	0.6036	0.3964
6	0.6036	0.3964	0.6036	0.3964

Table 2. The occurrence and nonoccurrence probabilities of earthquakes 6.0≤M≤6.4 (Region 2).
Çizelge 2. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (2. Bölge).

n	P_{11}	P_{12}	P_{21}	P_{22}
0	0.91000	0.09000	1.00000	0.09000
1	0.91810	0.08190	0.91000	0.09000
2	0.91737	0.08263	0.91810	0.08190
3	0.91744	0.08256	0.91737	0.08263
4	0.91743	0.08257	0.91744	0.08256
5	0.91743	0.08257	0.91743	0.08257
6	0.91743	0.08257	0.91743	0.08257

Table 3. The occurrence and nonoccurrence probabilities of earthquakes 6.0≤M≤6.4 (Region 3).
Çizelge 3. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (3. Bölge).

n	P_{11}	P_{12}	P_{21}	P_{22}
0	075000	0.25000	0.67000	0.33000
1	0.73000	0.27000	0.72360	0.27640
2	0.72840	0.27160	0.72789	0.27211
3	0.72827	0.27173	0.72823	0.27177
4	0.72826	0.27174	0.72826	0.27174
5	0.72826	0.27174	0.72826	0.27174

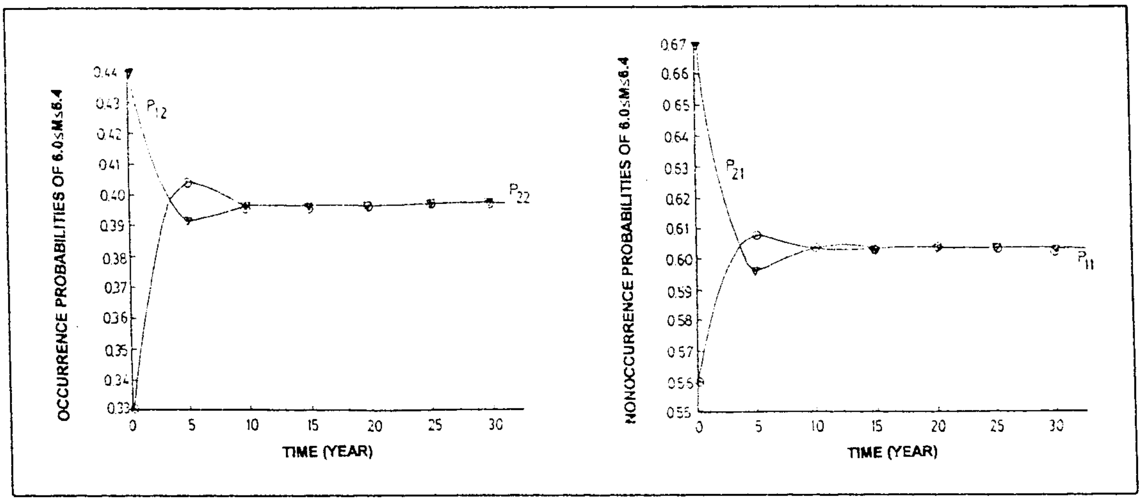

Fig. 6. The probability of the occurrence and nonoccurrence of the earthquakes 6.0≤M≤6.4 (Region 1).
Şekil 6. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (1. Bölge).

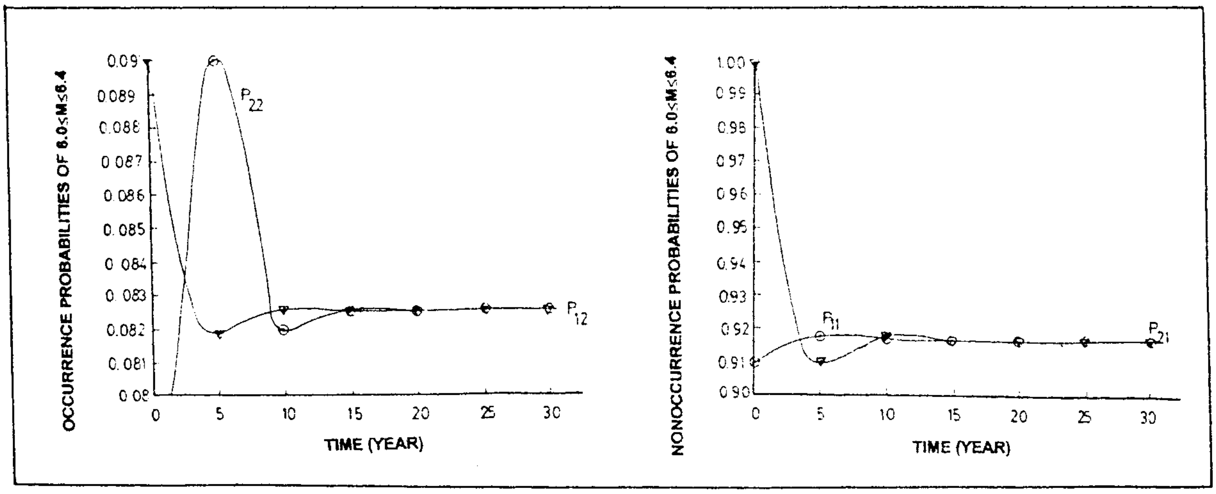

Fig. 7. The probability of the occurrence and nonoccurrence of the earthquakes 6.0≤M≤6.4 (Region 2).
Şekil 7. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (2. Bölge).

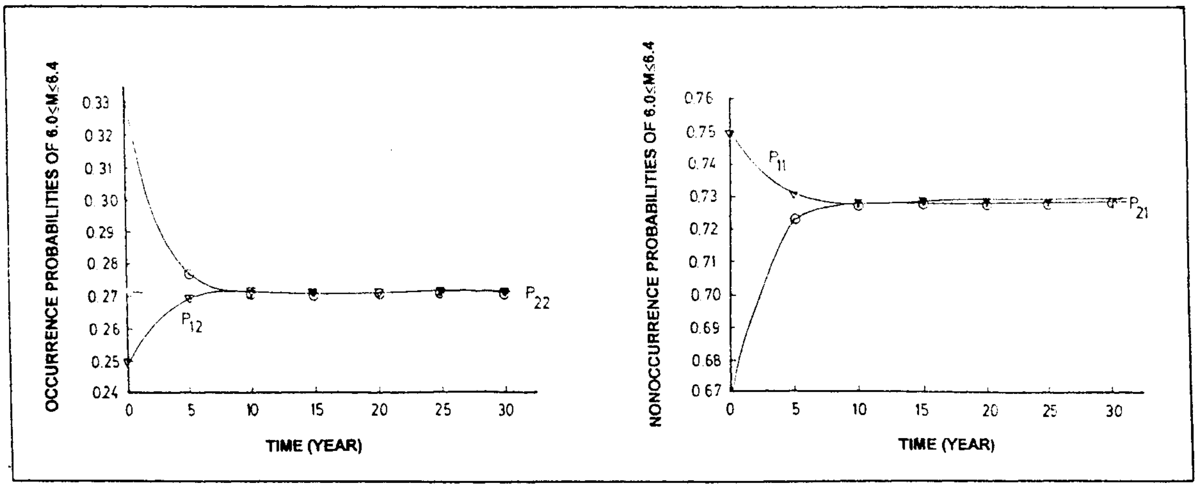

Fig. 8. The probability of the occurrence and nonoccurrence of the earthquakes 6.0≤M≤6.4 (Region 3).
Şekil 8. 6.0≤M≤6.4 depremlerin olma ve olmama olasılıkları (3. Bölge).

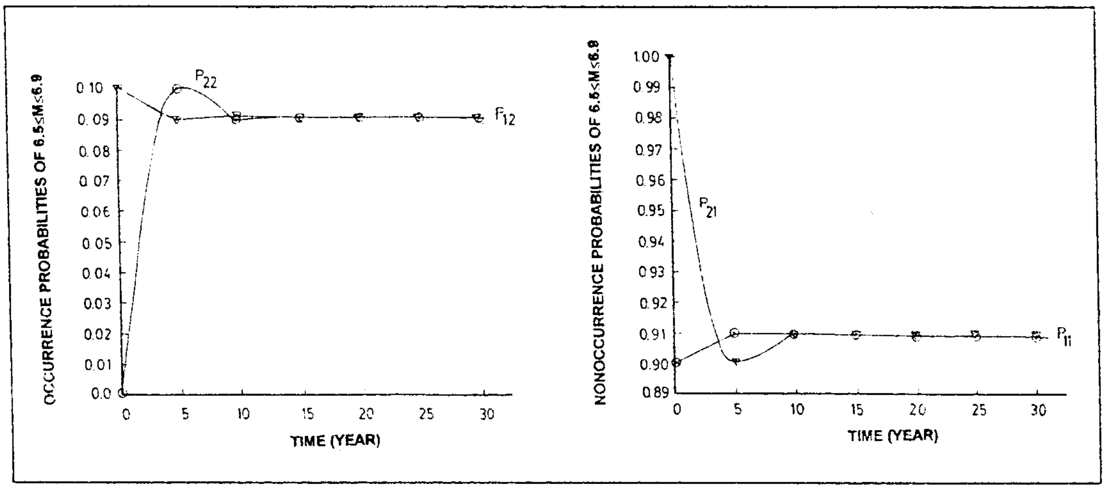

Fig. 9. The probability of the occurrence and nonoccurrence of the earthquakes 6.5≤M≤6.9 (Region 1).
Şekil 9. 6.5≤M≤6.9 depremlerin olma ve olmama olasılıkları (1. Bölge).

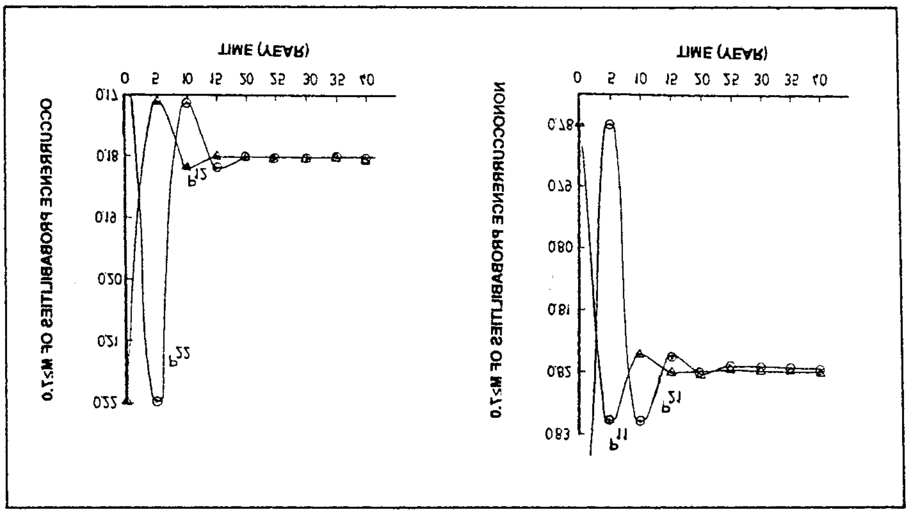

Fig . 10. The probability of the occurrence and nonoccurrence of the earthquakes M≥7 (Region 1).
Şekil 10. M≥7 depremlerin olma ve olmama olasılıkları (1. Bölge).

sence of a great earthquake in previous time interval, the occurrence probabilities of great earthquake is low. If there is a great earthquake in previous time interval, the probability of the occurrence of earthquake is high in subregions for next time intervals. In Region 1, for magnitude group 6.0≤M≤6.4, if there is no great earthquake in previous time interval, the occurrence probability of earthquake is found to be 0.44 in next time interval while the non-occurrence probability of earthquake is 0.56. If there is an earthquake in previous time interval, the occurrence probability of earthquake is 0.33. For other magnitude interval, 6.5≤M≤6.9, the occurrence and non-occurrence probabilities are presented in Figure 9. In view of this figure, when there is a great earthquake in previous time interval, the occurrence probability of earthquakes (6.5≤M≤6.9) is found to be 0.91 in next time intervals.

Transition probability matrices are obtained by transition probabilities of magnitude groups. Occurrence and non-occurrence probabilities of magnitude groups are obtained from transition probability matrices. For example, for Region 1, transition probability matrices for M≥7.0 at previous time period (1995) is obtained as:

$$P=\begin{bmatrix} 0.78 & 0.22 \\ 1.00 & 0.00 \end{bmatrix}$$

From this transition probability matrices occurrence and non-occurrence probabilities of earthquakes M≥7.0 are obtained and presented in Figure 10. For example, the occurrence probability of great earthquakes (M≥7.0) is found as 0.18 in the next 20 years if there is no great earthquake in previous time interval. If there is an earthquake in previous time interval, the non-occurrence probability of the earthquakes ($M \geq 7.0$) is found as 0.82.

With the application of Markov model for earthquake occurrences in Western Anatolia, the reasonable agreement is observed between the calculated probabilities and magnitudes in the future time intervals. The probability values of different magnitudes and time intervals are influenced in part by the accuracy and completeness of the historical seismicity record with respect to location and magnitude. Careful re-evaluation of the data should be made before applying the model to a specific area.

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