EUROPEAN EARTHQUAKE ENGINEERING

JOURNAL OF EUROPEAN ASSOCIATION FOR EARTHQUAKE ENGINEERING

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PATRON EDITORE

Seismic Expectancy Modeling of Northwestern Saudi Arabia

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SUMMARY – Seismic expectancy modeling of northwestern Saudi Arabia utilized the spatial distributions of the seismicity parameters of the magnitude-frequency relation. The spatial distributions are at every degree latitude and longitude comprising the 4×3 degree compartment. Contour maps of iso-a and b values and expected magnitude at 10% probability of exceedance in 50 years were drawn. The map of expected magnitude agrees to some extent to the recent seismic activities and probabilistic estimates of seismic hazards in the region particularly in the gulf of Aqabah. Likewise, the a and b-value distributions were also in conformity with the oceanic and continental tectonics of the region, which show that the continental areas are highly active with small scale events and the oceanic areas are prone to strong and major earthquake events. Basically, the applied methodology has some level of appropriateness and provides an adaptive approach to physically reliable estimates. Significantly, the study provides a preliminary basis for future occurrences of earthquakes of concern for northwestern Saudi Arabia and the probable identification and delineation of its seismic source areas.

KEYWORDS: Seismic Expectancy, Saudi Arabia, Seismic Hazard, Poisson Distribution.

1. Introduction

The oceanic portion of northwestern Saudi Arabia is one of the three geo-tectonic provinces comprising the southern portion of the Dead Sea transform fault /1/. The gulf portion is about 180 km long and about 15-25 km wide. The gulf forms the southernmost section of the NNE trending transform fault. The continental portion of NW Saudi Arabia is a stable region with numerous lineaments and two major faults trending in a NNW direction. The sudden and abrupt movements of the faults in this region may generate seismic hazards that can caused considerable damage to all vulnerable elements in the affected areas. Hence, the different geological structural formations in the area are considerable seismic risks to northwestern Saudi Arabia and to its socio-economic developments. Thus, it is imperative that seismic activities in space-time in these areas and their effects be given considerable study for seismic hazards reduction and preparation.

Historically, NW Saudi Arabia is seismically active as inferred from different source of seismic catalogues /2/, /3/, and /4/. The seismic activities along the gulf seem to be characterized by swarm and mainshock-aftershock types /5/. The series of earthquake events in the years 1983, 1984, 1985, 1988, 1990, 1993 and 1995 seemed to be of the swarm type. On land earthquakes such as the 1068 and 1588 events were of tectonic origin. Depth of foci in this area were reported to be from 1-27 km which suggests that lithospherical deformations are restricted to the crust /1/.

Since the aspect of the present study is toward disaster mitigation from occurring earthquakes of concern, it is deemed appropriate that primary attention should be focused on the expectation of these events. However, the constraints involved such as insufficiency of longer period of quality instrumental seismic observation, reliability of database and variety of opinions on the tectonic aspect of the area may yield conservative results. Therefore, the expectancy modeling in this study is confined within the allowable limitations of the utilized data.

Earthquake occurrences are considered random events in space-time so that their appropriate treatments are assumed to be under the domain of statistics and probability. Subsequently, the study and modeling for NW Saudi Arabia were based on this notion.

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Received june 1997. Revised november 1997.

2. Data sources and treatment

The area of interest for this investigation is defined by the coordinates 25° to 29° N latitude and 34° to 37° E longitude. It incorporates the NW portion of Saudi Arabia and gulf of Aqabah (fig. 1). The time coverage of the seismic data is from 1900 to June 1997. The recent seismicity (mb > 3) of the study area for the period from 1990 to 1997 is shown in fig. 1. This study utilized the catalogues of the preliminary determination of epicenters (PDE) of the USGS, international seismological center (ISC) and the seismological- geophysical observatory of King Saud University as the primary sources for the instrumental seismicity (1965-1997). The catalogues of Ambraseys et. al. /6/, Ben-Menahem /3/ and Poirier and Taher /4/ have been served as the primary sources for historical seismicity (1900-1964). Entries were cross-checked and additions made from various sources of earthquake records to insure that duplications are not included.

The magnitude scale preferably used in this study was the body wave magnitude (mb) for consistency. Hence, given surface wave magnitudes and epicentral intensities were converted to mb through the relations found by this study. Duration and local magnitudes were assumed to be equal to mb for moderate earthquake events.

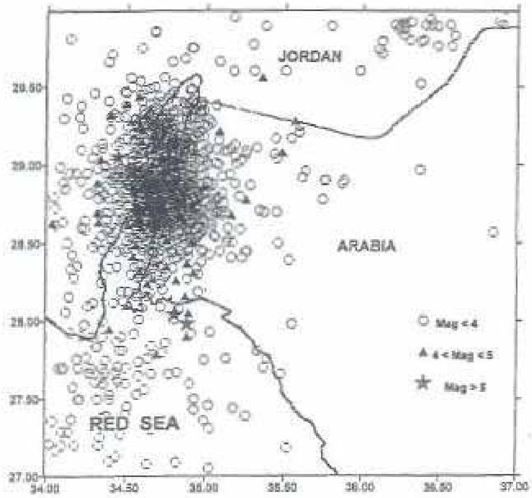

Fig. 1 – Location map of the study area in NW Saudi Arabia showing recent seismic activities from 1990 to 1997.

3. Methodology

The expectancy modeling were based from the earthquake recurrence concept and Poisson probability distribution. Firstly, the seismicity parameters were determined for each of the degree latitudes and longitudes comprising the modeled region which are the centers of a moving 4×4 degree source area from Hattori's method /7/ as follows:

3.1. Earthquake recurrence

The seismicity parameters are obtained from the temporal distribution of magnitude in a given area which are the constants of the magnitude-frequency relation. Applying the maximum likelihood estimate method developed by Utsu /8/ and Aki /9/, seismicity parameters were given as follows:

$$b = \log(e)/(Ma-Mo) \quad (1)$$

$$a = \log N + b*Mo \quad (2)$$

where:
N is the number of events equal and larger than Mo
Ma is the average magnitude
Mo is minimum magnitude and
(e) is the base of natural logarithm.

The method allows at least a minimum number of 4 observations in a given set of data /10/. This method was selected in view of insufficiency of data in the region. The application of this method in each square degree in the study area is preferable, however, scarcity of seismic data in some square degree compartment may reflect biased results and affects the actual seismicity. To avoid this situation, a moving 4×4 degree block was utilized as data source area /7/. The centers of the moving block were the latitudes and longitudes of the 4×3 degree compartment and each center is assumed to represent the location of the seismicity parameter for each respective block. The movement of the block is one degree interval in the latitudinal or longitudinal direction. The application of this method requires that the area coverage of the data source should be from 23-31° N latitude and from 32-39° E longitude. Since each square degree in the block is used 16 times utmost /7/, the values of the parameters obtained in the 4 corners of a 1×1 degree area may well represent its representative parameters values.

Since most of the magnitude data in the study area before 1965 were given in Ms and in terms of epicentral intensity (Io), there was a need for conversion for the two parameters for data homogenization. The empirical relations were applied respectively as follows:

$$mb = 0.87*Ms + 0.79 \quad (3)$$

and/or

$$mb = 0.93*Ms + 0.44 \quad (4)$$

and

$$mb = 0.45*Io + 2.77 \quad (5)$$

Equations (3) and (5) were the results from 62 and 22 samples from the Red Sea and adjacent regions respectively. Equation (4) developed by Al-Amri /11/ for southern Red Sea region.

3.2. Poisson distribution

Of importance in this study is the expected occurrences of earthquake events whose magnitudes are of concern. Given that earthquakes are random phenomena, then their occurrences are best described by probability concepts. The adverse effects of earthquakes generally come from significant events. Hence, their occurrence in time is of concern. The random distribution of large scale seismic events is known to fit the Poissonian probability distribution in time. The distribution is given by

$$Pn = ((h*t)^n*exp(-h*t))/n! \qquad (6)$$

where:

Pn is the probability of occurrence of n events in a given time interval (t), h is the mean rate of occurrence and n! is factorial. When no events of interest occur during a given interval of time (t), equation (6) becomes

$$Po = exp(-h*t) \qquad (7)$$

However, if at least one event of interest happens during the time t, then the assumed risk (R) or probability of exceedance from the assumption of non-occurrence is

$$R = 1 - exp(-h*t) \qquad (8)$$

The mean rate of occurrence of earthquake events in the study area is estimated from the magnitude-frequency relation

$$N(M)/T = (N/T)*10^{\wedge} - b(M - Mo) \qquad (9)$$

where M is the magnitude equal and larger than a given value of interest, N is the number of events equal and larger than Mo, and T is the time coverage of the utilized data. The expected number of occurrences of M in time interval (t) is

$$N(M)*t/T = N*t/T)*10^{\wedge} - b(M - Mo) \qquad (10)$$

Assuming that earthquake occurrences in the modeled area satisfy Poisson's equation, then the mean rate from (9) or expected number of occurrences from (10) is acceptable for substitution in (8). Substitution of equation (9) or (10) in (8) yields a function of M that is dependent on R and time (t) upon simplification, that is,

$$M = Mo - (1/b)*Log(-T*Ln(1 - R)/(N*t)) \qquad (11)$$

With given values of R and t, the corresponding expected magnitude value (M) can be estimated. Usually, 10% for R and 50 years for t are substituted.

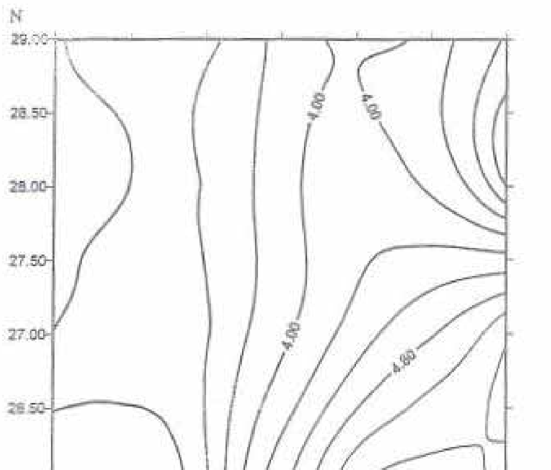

Fig. 2 – Spatial distributions of the seismicity parameters «a» per year at every degree latitude and longitude.

4. Results and Discussion

Equations 3 and 4 almost gave equal values for corresponding magnitudes. These two equations show that for conversion of larger Ms to mb give values which are almost equivalent to the given Ms value such that no attempts were made to calculate the seismicity parameters in terms of Ms.

The minimum magnitude (Mo) considered for the calculation of the seismicity parameters in each moving block whenever available was 4.0. The magnitude increment was 0.1. Calculations for the values of the parameter «b» were allowed to vary with magnitude starting with the Mo. The value of «b» for each center was selected when there seemed to be the tendency of leveling or stability with the magnitude /7/. The values of «a» were taken corresponding to the values of «b» and were respectively plotted in each degree latitudes and longitudes of the modeled area. The results shown in figs. 2 and 3 where iso-curves were drawn on the basis of the plotted values to account for their spatial distributions.

The range of «b» as obtained from equation 1 was from 0.89-1.41. This range is in general agreement with those advocated by Thenhaus et al. /12/ which gave from 0.89-0.92 for transform fault; 1.01-1.04 for non-transform; 0.89-1.11 for continental; and for combined categories from 1.0-1.11 for Saudi Arabia. The rectangular block 27-29° N; 34-35° E indicates «b» values from 0.88 to 0.93 which are indicative for oceanic transform faults and mobile earthquake generating structures. The continental portion of northwestern Saudi Arabia has the «b» values from 0.89-1.41. These values are observed in young platforms and in crustal

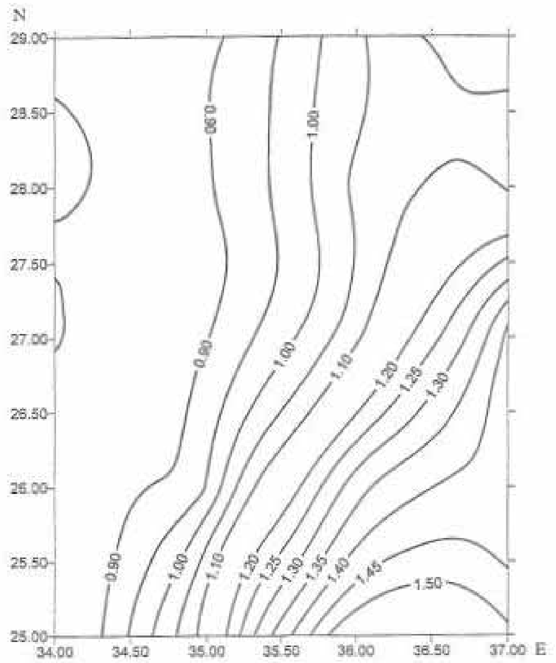

Fig. 3 – Spatial distributions of the seismicity parameters «b» per year at every degree latitude and longitude.

materials with high degree of heterogeneity /13/.

The Arabian shield is believed to have been formed by successive accretions of enigmatic island arcs composed of several cycles of metavolcanic, metasedimentary and plutonic rocks. El-Isa and Al-Shanti /1/ proposed that the shield has been formed from micro-plate accretions. Accordingly, the high «b» value (> 1) indicates high seismic activity for small events. The presence of many lineaments in the continental portion of the study area lent support to the «b» values obtained thereat.

Fig. 3 shows that the «b» values distribution agrees with the tectonic structures in the area. Above 27° N latitude, the range of «b» value from 0.9 to 1.05 are oriented almost in a N-S direction in alignment with the Dead Sea transform fault system. Below 27° N latitude, the iso-b curves are in NNE direction which are in alignment with the assumed movement of the Arabian Peninsula and transform faults located along the northern Red Sea. The spacings of the contour curves to the right side of b = 0.9 are closer compared to the left side. The left side of fig. 3 is principally dominated by one main seismic source which is the southern Dead Sea transform, while the right side is composed of many secondary seismic sources. It is not clear at present whether this is due to extensional tectonics from the Red Sea rift system. However, it seems that the iso-curve value b = 0.9 divide the study area into two blocks or seismic zones. It is also probable that the high «b» value on the continental part of NW Saudi Arabia may be due to insufficiency of seismic data. The expected magnitude value in each latitude and longitude of the study area was obtained from equation 11 with R = 10% and t = 50 years. The results were plotted in their respective locations from which contours of iso-magnitude curves were drawn as shown in fig. 4. It can be seen that the one square degree area (28-29° N; 34-35° E) is almost covered by an iso-curve of mb = 7.0 which from equation 1 or 2 gave approximately Ms = 7.1. It is worthwhile to mention that the 22 Nov. 1995 Aqabah earthquake was located in that compartment and has the magnitude Ms = 7.1 (USGS). The general agreement in location and magnitude may indicate an appropriateness of the model and representativeness of the quality of the utilized data and assumptions.

Thenhaus et al. /12/ assigned maximum magnitude for oceanic transform of Ms = 7.2 with correction of 0.25 unit, while Al-Haddad et al. /14/ indicated that the maximum credible magnitude for the gulf of Aqabah is 7.5. Using their respective assigned maximum magnitude in their studies, Thenhaus et al. /12/ obtained probabilistic estimate of 0.4-0.45g peak ground acceleration (pga) at 90% non-exceedance in 100 years, while Al-Haddad et al. /14/ got 0.2g (pga) at 10% exceedance in 50 years at distances of 20 km and 60 km respectively for the Aqabah source area. For the same attenuation model and pga value obtained by Al-Haddad et al. /14/, the Ms = 7.1 gave a distance of 40 km. For t = 100 years, the present model gave Ms = 7.4. This magnitude value is almost the same with Thenhaus et al. /12/ when the correction is added. From their attenuation model and at the same pga value, they gave also a distance of 20 km for the present model. Since the shape of the Ms = 7.1 and Ms = 7.4 iso-curves would be the same and cover their assumed seismic zones for Aqabah, these magnitude values are within the range of their obtained pga's and in agreement with the present model. In comparison with their respective values from the Nov. 22, 1995 earthquake, the results from this study give better estimate. Iso-magnitude curve interval of 0.25 unit (Fig. 4) shows a closer spacing of decreasing iso-magnitude curves to the right of mb = 7.0 which is in good agreement with the spatial distribution of the «b» value. The presence of probable seismic sources in the area like secondary transform faults assumed from heat and magnetic flow studies in the northern Red Sea and tectonic lineaments on the continental portions of NW Saudi Arabia could explain the close spacings of the iso-curves and decreasing magnitude values toward the land areas.

The Dead Sea transform fault system is a major tectonic feature in the gulf of Aqabah and has been active since historical time. Because of this distinctive quality, the occurrence of large scale events is expected and quantified based from estimates on its fault length and historical activities. The expectation and quantification were in general agreement with our model.

The historical earthquakes of Ms = 6.7 (1588) and Ms = 7.0 (1068) were located by Ambraseys /6/ within the rectangular area (27-29° N; 34-35° E) where segments of two major tectonic faults trending NNW are also located. Although these two historical earthquakes were not incorporated in the analysis, their occurrence in the future is a concern for NW Saudi Arabia. Since the return time of the drawn map of magnitude is ap-

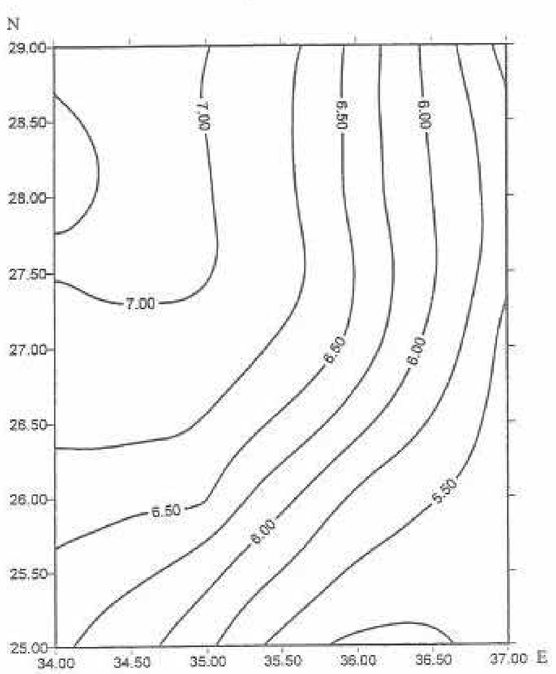

Fig. 4 – Expected magnitude at 10% probability of exceedance in 50 years.

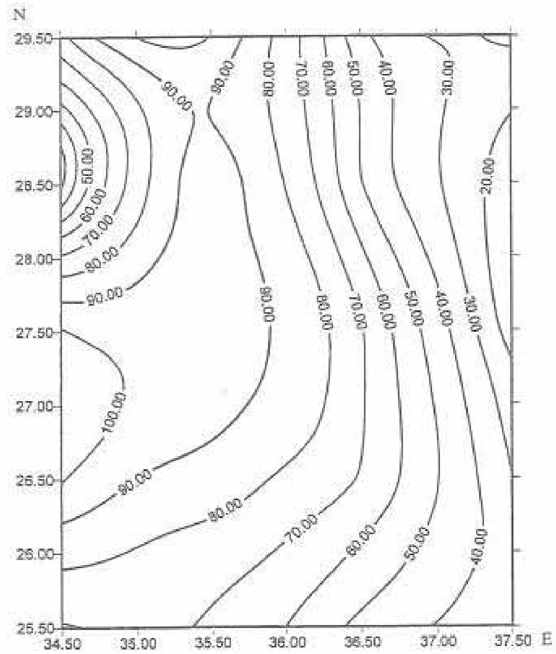

Fig. 5 – Seismic hazard from observed maximum magnitude in 1×1 degree compartment.

proximately 475 years, the expected magnitude values obtained along longitude 36° E and latitudes 27-29° N can probably account for these two historical earthquakes which seemed that the 1068 event has re-occurred in 1588 allowing influences of time and space variables for the mechanism. Whether this supposition is actually supported firmly by the model is uncertain due to scarcity of instrumental data in this area. The presence of the tectonic faults in this area requires corresponding intensive efforts for earthquake monitoring. This area is a continental portion of Saudi Arabia and the propagation of the seismic waves in the continental parts is of high quality /6/. Future socio-economic developments in this region should reckon the effects of expected seismic hazards which as indicated in this study shows a certain degree of precision in some areas.

In the aspect of recurrency, the observed maximum earthquake in each one square degree compartment in the study area is important for future reduction of seismic hazards. Calculated seismic hazard for the historical earthquakes of 1068 and 1588 gave 49.4% and 42.7% respectively. Since the probability of exceedance is approximately 67.3%, there is possibility that either one of these two earthquakes may occur in the near future.

The calculated probability of occurrence of the observed maximum earthquake in the other compartments indicate higher values as shown in fig. 5. It can be seen that the highest percentage that the maximum observed earthquake can be exceeded in the near future occurs along a strip which is almost in the middle portion of the study area.

Generally speaking, The expectancy seismic hazard map has been prepared for an attempt to make preliminary bases for future occurrences of earthquakes of concern in NW Saudi Arabia and probable identification and delineation of seismic source zones. Most of the studies conducted by Thenhaus et al. /12/; Al-Amri /15/ and Al-Haddad et al. /14/ in this area have been based primarily on arbitrary zonation and the application of the magnitude-frequency relation. Whereas, this study endeavors to present an adaptive method for physically reliable results and basis which can also be applied in other areas of seismic concern.

5. Conclusions

The spatial distribution of the seismicity parameters for NW Saudi Arabia were determined using the maximum likelihood method with a moving data source area. The distributions were at every degree latitude and longitude of the study area. The obtained values of the parameters were assumed to fit the Poissonian probability distribution from which the expected magnitude in 50 years time at 10% probability of exceedance were calculated. Results show that to some degree of precision the expected magnitudes were agreeable to recent seismic activities and probabilistic estimate of seismic hazards particularly in the Aqabah region. Hence, this can be taken as an appropriateness of the applied methodology and reasonableness of the assumptions. Significantly, there were two aspects that were preliminarily developed and these are the future occurrences of earthquakes of concern in NW Saudi Arabia and the preparation for the probable identification and delineation of seismic source zones.

The application of the aforementioned method is the first of its kind in the study region, nevertheless, there are strong indications of accuracy from the results that the modeling is significantly appropriate. The results were generated from an adaptive method from the physically reliable point of view which could also be applied to other areas of seismic concern for its further validation.

Acknowledgment

We gratefully acknowledge the assistance provided by our colleagues at the Seismological-Geophysical Observatory of King Saud University.

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