Preliminary seismic hazard assessment of the southern Red Sea region

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SUMMARY – The present work represents an attempt to assess the probabilistic earthquake hazard in the southern Red Sea region and to stimulate discussion and suggestions on the assumptions. The resultant uncertainties are due primarily to the lack of strong motion records, lack of instrumental data, incompleteness of catalogues and the complexity of the seismotectonic environment.

Based on the geotectonic and seismic considerations, two seismic area sources are delineated. For each individual seismic source, recurrence relationship regression constants and maximum magnitudes are provided. Poisson stochastic model and an appropriate attenuation relationship are involved. The results of analysis are presented in the form of Iso-acceleration maps for the return period of 475 years.

The results obtained from this study indicate that relative level of ground motion in southern Red Sea is found to be moderate and subjected to more severe seismic hazard compared with the Arabian Shield.

KEYWORDS: Seismic Hazard, Red Sea, Arabian Shield, Seismotectonics, Ground – motion.

1. Introduction

The seismic hazard can be defined as the probability of occurrence at a given place and within a given time period of ground motion due to an earthquake of a particular size capable of causing significant damage. The probability that a certain peak ground acceleration at a site will be exceeded, depends on the probabilities that earthquakes of different magnitudes will occur and will induce this ground acceleration or a higher value. Hence, it is here suggested that the assessment of the probabilistic seismic hazard requires all the available information on seismicity, tectonics and regional attenuation characteristics of the ground motion as well as the adoption of a stochastic model for the forecasting of future occurrences. Seismic hazard maps produced by Thenhaus et al. /1/, for Western Arabia and those of Al-Haddad et al. /2/ for the Arabian Peninsula and its vicinity, give contours of accelerations (or velocities) having a 90 per cent probability of not being exceeded in time periods of 50 and 100 years.

The area of interest for this investigation is defined by the coordinates 15°-20° N. latitude and 39°-45° E. longitude. It incorporates the southwestern part of the Arabian Peninsula and the southern Red Sea (Fig. 1).

The importance of conducting this study is due to

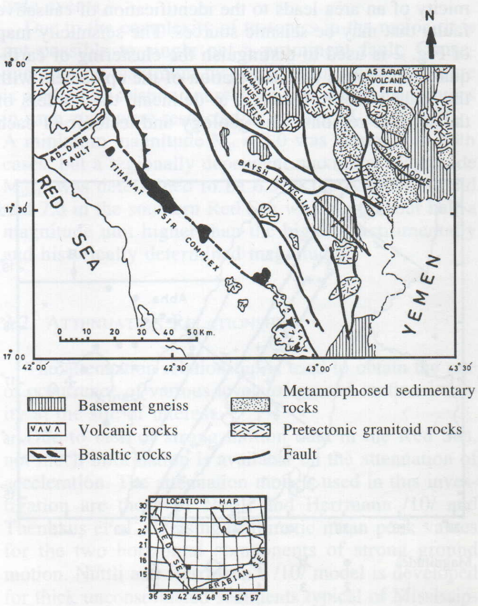

Fig. 1 – Tectonic map of the southern Arabian Shield and Red Sea showing major tectonic features.

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the fact that earthquake hazards are high in the southern Red Sea compared with the rest of Saudi Arabia. The occurrence of the January 11, 1941 earthquake (M_s = 5.8; Ambraseys and Melville /3/) and the 1982 Yemen earthquake of magnitude 6.0 /4/ brought to attention the hazards that may results from nearby seismic sources. Consequently, more studies were carried out on local seismicity and seismic hazard assessment of Western Arabia and the Red Sea (Merghelani /5/; Barazangi /6/; Thenhaus et al. /1/; El-Isa and Al-Shanti /7/; Makris et al. /8/; Al-Haddad et al. /2/; Al-Amri /9/).

The purpose of this study is an attempt to apply different empirical relationships and models for estimating the seismic hazard in the southern Red Sea. In order to achieve this goal, this study collected the available historical and instrumental seismic data from different catalogues. Al-Amri /9/ utilized these data in conjunction with geologic and magnetic information, in interpreting the seismotectonics of the southern Red Sea region. Based on the existing geologic and seismotectonic implications, two seismogenic zones were delineated. Employing the attenuation relationship (Nuttli and Herrmann /10/; Thenhaus et al. /1/), the probability of peak ground acceleration was developed by STASHA /11/ to construct hazard curves and iso-acceleration maps for different return periods.

2. Seismic source regionalization

Potential seismic sources are defined on the basis of geologic and seismic data. An understanding of the regional tectonics, local Quaternary history and seismicity of an area leads to the identification of causative faults that may be seismic sources. The seismicity map of Fig. 2 is used to distinguish the clustering of earthquake epicenters and association of the epicenters with the main tectonic features, to delineate the borders of the seismic regions. The geology and tectonic of each

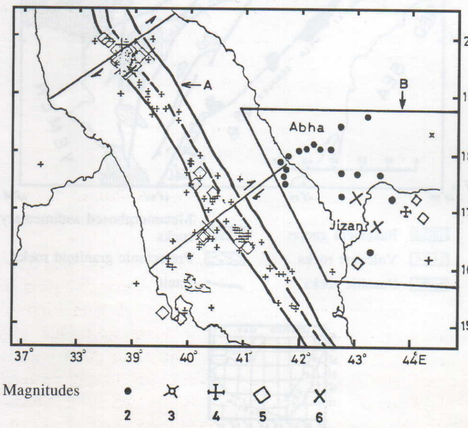

Fig. 2 – Seismic source regionalization map showing epicentral distribution.

cluster are studied to identify the boundaries of different zones assuming that all events have shallow focal depths.

Analysis of the epicentral distribution in conjunction with major tectonic features suggests that there are two seismic source regions which may be delineated namely, southern Red Sea (area A) and southern Arabian Shield (area B). Spatial distribution of Historical and instrumental seismicity was employed to group the data in such a way that inside each region the earthquake process displays a reasonable statistical homogeneity. Tectonic and geologic analyses of each area can be summarized as follows:

2.1. Southern Red Sea

The Red Sea which separates the Arabian Shield from the Nubian Shield is considered as one of the world's youngest oceanic basins. The opening of the Red Sea has resulted in the development of tensional tectonics along the western margin of the Arabian plate.The narrow, axial trough of the Red Sea is generally accepted as a divergent plate margin, the locus of sea-floor spreading associated with the separation of Africa from Arabia /12/. Axial magnetic anomalies indicate that new oceanic crust has been forming for approximately the last 4-5 m.y. at a sea floor spreading have rate of about 1 cm / year /13/. Le Pichon and Francheteau /14/; Bonatti /15/ propose that the oceanic crust is restricted to the area beneath the main and axial troughs, and an attenuated continental crust exists beneath the Red Sea shelves.

Structural deformation is intense in the axial zone and characterized by numerous normal faults. Marginal to the axial trough, deformation of the main trough is less intense but also characterized by normal faults /16/.

Geological evidence indicates that during the Oligocene and Miocene, the Red Sea developed as a depression rather than as a down-faulted block. However, the axial trough developed during the Pliocene as a rift structure, similar to a typical mid-ocean rift valley /12/. A remarkable correlation exists between historical earthquakes in the past 2000 years and geological evidence of Quaternary tectonic movements /17/. The majority of earthquakes and tectonic activities are concentrated along the belt which extends from the central Red Sea region south of Afar and then east through the Gulf of Aden. The distribution of the shallow focus earthquakes /18/ indicates that the axial trough is an area of active spreading.

Recent microearthquake studies by Makris et al. /8/ using ocean-bottom seismographs (OBS) in southern Red Sea (Suakin Deep) indicate that the deformation and mobility of the crust is extremely high and the stresses are released by numerous small displacements rather than few large earthquakes.

2.2. Southern Arabian Shield

Evolutionary models of the Arabian Shield currently favor collisional accretion of multiple plates or plate fragments. Along its western border with the Red Sea, the shield is characterized by widespread Tertiary and Quaternary volcanism, mafic igneous dikes of Miocene /19/. This volcanism seems to be associated with sea-floor spreading in the Red Sea.

The shield consists of two 20-km-thick layers of crust with an average P-wave velocities 6.0 and 7.0 km/s in the upper and lower crust respectively. This crust thins abruptly to less than 20 km in the SW, where Precambrian outcrops abut the Cenozoic rocks /20/.

An important aspect of the tectonics of the Red Sea-Western Arabia region is the presence of many NE trending transform faults along the Red Sea rift system. Marine and land magnetic studies indicate that some of these transform faults may extended inland and displace prominent upper Cenozoic structural features /19/.

The scarcity of instrumentally located earthquakes in Western Arabia should not be regarded as evidence of negligible seismic hazard /6/. Focal mechanism studies indicate strike-slip movement along NE trending planes that seems to be associated with the rift transform faults /18/. Structural pattern inferred from land magnetic data provide evidence for continuation of the faulting regime into the Arabian Shield /13/. If these NE faults are active, then seismic hazard in Western Arabia may be significant. An earthquake of magnitude 6.2 occurred on January 11, 1941 near 17° N, 43° E, about 30 km east of the city of Jizan /21/; there was an aftershock of magnitude 5.5 on February 4, 1941.

More recently, the occurrence of the 1982 and 1991 north Yemen earthquakes of magnitudes 6.0 and 5.4 respectively, could imply that the north Yemen is a region of moderate to high seismic hazard. This region shows a series of normal faulting that results in horst-and-graben structure and Holocene to recent basaltic volcanism. In southwestern Arabian Shield (north of Jizan) a high level of seismic activity was reported by Merghelani /5/. He located fourteen events that ranged in magnitudes from 1.4 to 2.5.

3. Earthquake Data Processing

3.1. Data Treatment

In order to assess and estimate the seismic hazard in the southern Red Sea, this study utilized the catalogues of the National Earthquake Information Center (NEIC), U.S.Geological Survey and the International Seismological Center (ISC) as the primary sources for the instrumental seismicity (1965-1994). The catalogues and bulletins of Gutenberg and Richter /21/; Ambraseys and Melville /3/; Ambraseys /17/ have been served as the primary sources for historical seismicity (1900-1964). Local earthquake data for the period 1988-1994 were obtained from the seismological observatory, King Saud University, Riyadh. Entries were cross-checked and additions made from various sources of earthquake records to insure that duplications are not included.

As previously stated, the two seismic sources in this study were modeled as area source based on geotectonic and seismic evidence. For each area source, the frequency – magnitude analysis was carried out utilizing the Gutenberg and Richter /21/ equation:

$$\mathrm{Log}N = a - bM$$

where N is the number of events of magnitude M or greater; a and b are constants depending on tectonic factors such as the nature of faulting associated with the earthquakes.

The earthquake catalogues are often biased due to incomplete reporting for small events, especially pre 1965. Treatment of the incompleteness was applied using the earthquake detection and reporting probabilities /22/. These probabilities are allowed to vary in time-span and with the size of the earthquake. The number of events for a specific magnitude range are adjusted to reflect the probability of the detection and reporting. The rate of occurrence of the magnitude is then evaluated based on the time span over which it is observed to occur.

The determination of the maximum magnitude expected in a source zone is a difficult and quite subjective problem. Thenhaus et al. /1/ indicated that the ground-motion estimates of the Western Arabia are not critically sensitive to the choice of maximum magnitudes. Because of the low level of seismicity in this region, the ground-motion values are well below the near-field ground-motions produced by the chosen maximum-magnitude earthquakes. Hence, the ground motions for short return periods are dominated by the more frequent occurrence of low – to moderate-magnitude events.

Due to the complexity of tectonics in the region, it is not possible to single out a prominent fault. Consequently, the maximum historical earthquake procedure is applied to seismic sources. In this study, magnitudes in each zone were restricted to a range $M_0 < M < M_{max}$. A minimum magnitude $M_0 = 3.0$ was assumed in both cases, but a regionally dependent maximum magnitude M_{max}. was determined to be 6.5 in the Arabian Shield and 7.0 in the southern Red Sea which are about half a magnitude unit higher than the highest instrumentally and historically determined magnitudes.

3.2. Attenuation Relationships

The attenuation relationship is used to obtain the rate of occurrence of various levels of ground motion severity at the site of interest.

Due to lack of strong motion data in the Red Sea, not much information is available on the attenuation of acceleration. The attenuation models used in this investigation are those of Nuttli and Herrmann /10/ and Thenhaus et al. /1/ using arithmetic mean peak values for the two horizontal components of strong ground motion. Nuttli and Herrmann's /10/ model is developed for thick unconsolidated sediments typical of Mississippi embayment; a surficial geologic setting similar to the coastal region of western Saudi Arabia /1/. For m_b >

4.5, the relations for average mean peak horizontal acceleration (A_h in cm/sec^2) and velocity (V_h in cm/sec) are of the form:

$$\log A_h = 0.57 + 0.50\, m_b - 0.83 \log (R^2 + h^2)^{0.5} - 0.00069\, R$$

$$\log V_h = -3.6 + 1.0\, m_b - 0.83 \log (R^2 + h^2)^{0.5} - 0.00033\, R$$

Where:
R = the distance between the source and the site
h = the focal depth
m_b = body – wave magnitude

In our application of this model, depth solutions were judged unstable so the focal depth was fixed at 10 km,which is the average of the free depth solutions. The distance between the area source and site (Jizan) is about 200 Km.

The second attenuation relationship model applied in this study is the model recommended by Thenhaus et al. /1/ for Western Arabia and the coastal area of the Red Sea. This relationship is based on the empirical relation developed by Campbell /23/. Thenhaus et al. /1/ used Campbell's low-Q, 2-km-depth attenuation model for velocity and peak ground acceleration (A) as the «preferred model».

$$\ln A = -3.303 + 0.85\, M - 1.25 \ln \{R + 0.087\, e^{0.678M}\}$$

The standard deviation in ln A appears to be within a range of 0.35 to 0.65 and is generally assumed to be hold for all magnitudes and distances of Bender's /24/ relation. In this study, a standard deviation of 0.5 in ln A (either velocity or acceleration) is assumed in both models.

Using the aforementioned attenuation relationships, the hazard calculations from the two sources was derived by Shah /25/ using the step-by-step numerical procedure. This procedure was implemented by the Stanford Seismic Hazard Analysis computer program STASHA /11/ to construct hazard curves at Jizan and Abha sites and iso-acceleration maps for 10% probability of being exceeded in 50 years, which is equivalent to a return period of 475 years.

To perform seismic hazard analysis for predicting of future earthquakes, Poisson model is employed in STASHA program assuming that earthquakes are spatially and temporally independent. This model allows earthquakes to occur as areas within source zones assuming that earthquake occurrences have a Poisson distribution, that occurrence rate remains constant during the time period considered. This model has been found to be adequate for assessing the earthquake hazard in regions where earthquakes occur frequently and their magnitudes are intermediate or small /26/.

4. Discussion & Conclusions

Instrumental and historical seismicity provide significant information for evaluation of the seismic hazard in western Arabia. 180 earthquakes ($3.0 < m_b < 6.6$) are reported to have occurred in the period 1900-1994. About 85% of the activity occurred in the axial trough of the Red Sea and 15% in the southern Arabian Shield. Recent seismic activity /9/ indicates that some transform faults of the southern Red Sea are a few hundred kilometers long and run from the Red Sea into the shield causing considerable seismic hazard.

Analysis of the seismicity data from the southern Red Sea region (Fig. 2) in conjunction with other available magnetic /13/ and geologic information provide evidence for continuation of the faulting regime from the Red Sea northeastward into the Arabian Shield /9/. Local earthquake data from KSU observatory helped in defining the nature of faulting and locating some events in the shield area.

Due to the lack of strong motion data and the uncertainty in attenuation characteristics, we applied the aforementioned models with some modifications and compare it with previous models /1/; /2/. The seismic hazard information in this study is based on the recurrence relationships. It has found that a and b values for the southern Red Sea are 6.22 and –0.913 respectively. Thenhaus et al. /1/ estimated b-values to be between –0.89 and –1.11. The high average b-value at the southern Red Sea could be due to the heterogeneity in the lithosphere or the applied stress not being uniform.

The relationship between the PGA values and the exceedance probability (seismic hazard curves); the PGA and return period (acceleration zone graphs) are illustrated in Figs. 3 and 4, respectively. Fig. 5 shows the regional distribution of PGA for the whole study area with two sites marked on it (Jizan and Abha), having a 10% probability of being exceeded in 50 years. The contour levels range from 0.05 to 0.20 g. Below the 0.05 g level, the ground shaking effects are generally controlled by small magnitude events with unreliable recurrence rate and attenuation characteristics.

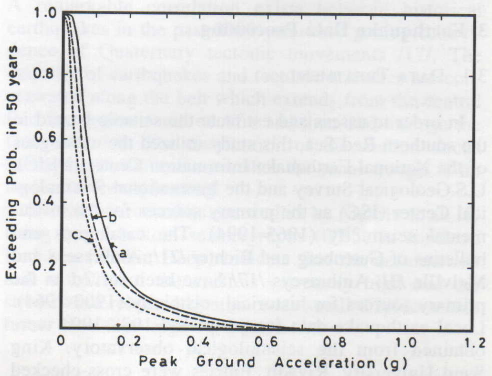

Fig. 3 – Seismic hazard curves (PGA Vs. exceedance probability) for 50 years exposure time. Curves a and b for Jizan and Abha cities, respectively (This study), whereas curve c for Jizan (From Al-Haddad et al. /2/).

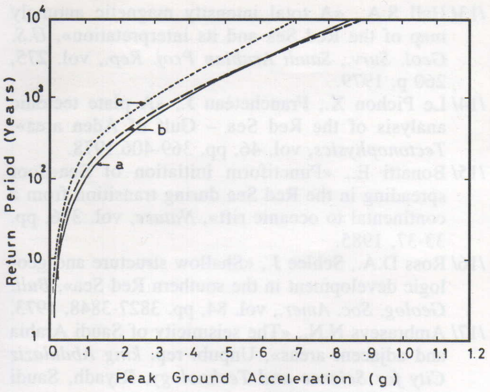

Fig. 4 – Acceleration zone graphs (PGA Vs. return period). Labels as indicated in Fig. 3.

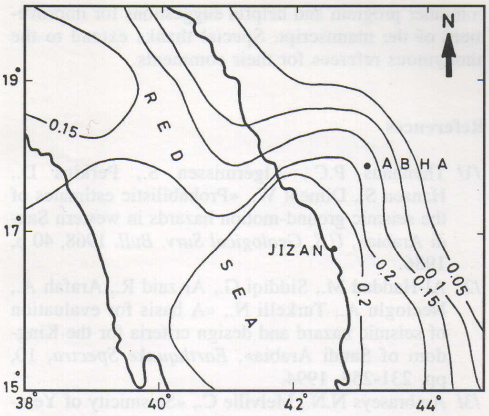

Fig. 5 – Iso-acceleration map for 10 % probability of being exceeded in 50 years. Contours are in gravity units.

PGA values were calculated to be 0.24 g at Jizan and 0.21 at Abha (curves a and b of Fig. 3, respectively, which are in good agreement with the results of Al-Haddad et al. /2/). They estimated the PGA value at Jizan site to be 0.18 g for the same time period of exceedance (curve c of Fig. 3). Thenhaus et al. /1/ indicate that PGA and horizontal velocity at Jizan having a 90 % probability of not being exceeded in 100 years are 0.13 g and 7 cm/sec, respectively.

Alternatively, probabilistic ground motion attenuation relations derived by Nuttli and Herrmann /10/ are developed for southern Red Sea for magnitudes > 4.5 assuming the largest probable earthquake will take place at the same epicentral distance of the actually observed largest earthquake. Historically, the largest earthquakes in the region (1921, 1941, 1955, and 1962) occurred at an average epicentral distance of 150 km from Jizan and Abha. It is assumed in this study that the largest probable earthquake will occur at an average epicentral distance of 200 km and focal depth of 10 km. The mean peak ground horizontal acceleration is found to be 24.3 cm/sec^2, the horizontal velocity is 7.6 cm/sec and the maximum observed value of the ground acceleration in both sites will rarely exceed 400 cm/sec^2. Thenhaus et al. /1/ used the high-Q Nuttli and Herrmann /10/ relations to estimate ground motion values in coastal region of the Red Sea. They found the PGA and horizontal velocity at Jizan to be 0.20 g and 8 cm/sec, respectively.

It is of particular interest in this study to note the large differences between the ground motion values in the two sites. Abha, located on the Arabian Shield indicates moderate ground motion values, whereas Jizan (on the coast) shows moderate to high values. Jizan is found to be subjected to more severe seismic hazard compared with Abha. The relatively high peak accelerations in Jizan are basically due to its close location to the seismic activity along the inferred transform fault in the southern Red Sea and also could be affected by large magnitude earthquakes in the zone of high seismicity in North Yemen (the occurrence of the January 11, 1941 earthquake, 75 km east of Jizan and 1982 earthquake).

The historical and instrumental records of strong shaking in the shield area (1832, 1845, 1941, 1982, and 1991) indicate that the return period of severe earthquakes, which affect the area is about 60 years, in average. Much of the seismicity is of the swarm-type which associated with the Quaternary volcanics of considerable seismic hazard. Marine epicenters (1921, 1962, 1967 and 1993) are less hazardous than those of land earthquakes because of the high attenuation of seismic waves travelling through the rather soft and hot upper mantle material beneath the sea. The 1993 earthquake (m_b = 6.0) that occurred in the central Red Sea caused no damage to the coastal areas.

Geologic and seismic evidence show some high level of seismicity associated with the NE-trending Ad-Darb fault (120 km, north of Jizan). If this fault is found to be seismically active, it could dominate the earthquake ground motion hazard at Jizan and Abha. More recently, Civil Defense (1993, personal communication) reported a sudden downhill vertical movement caused by water (landslide) nearby Ad-Darb fault. Understanding of the earthquake hazard would include a knowledge of the susceptibility of this area to induced ground failure.

Generally speaking, the present work represents an attempt in assessing the probabilistic estimates of the seismic ground motion hazard in the southern Red Sea region. Large uncertainties in our results and in previous work are due primarily to the lack of strong motion records, lack of instrumental data, incompleteness of catalogues and the complexity of the seismotectonic environment.

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