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Seismicity and Seismic Hazard in Alexandria (Egypt) and its Surroundings

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Abstract—Alexandria City has suffered great damage due to earthquakes from near and distant sources, both in historical and recent times. Sometimes the source of such damages is not well known. Seismogenic zones such as the Red Sea, Gulf of Aqaba-Dead Sea Hellenic Arc, Suez-Cairo-Alexandria, Eastern-Mediterranean-Cairo-Faiyoum and the Egyptian costal area are located in the vicinity of this city. The Egyptian coastal zone has the lowest seismicity, and therefore, its tectonic setting is not well known.

The 1998 Egyptian costal zone earthquake is a moderate complex source. It is composed of two subevents separated by 4 sec. The first subevent initiated at a depth of 28 km and caused a rupture of strike (347°), dip (29°) and slip (125°). The second subevent occurred at a shallower depth (24 km) and has a relatively different focal parameter (strike 334°, dip 60° and slip 60°). The available focal mechanisms strongly support the manifestation of a complex stress regime from the Hellenic Arc into the Alexandria offshore area.

In the present study a numerical modeling technique is applied to estimate quantitative seismic hazard in Alexandria. In terms of seismic hazard, both local and remote earthquakes have a tremendous affect on this city. A local earthquake with magnitude $M_s = 6.7$ at the offshore area gives peak ground acceleration up to 300 cm/sec^2. The total duration of shaking expected from such an earthquake is about three seconds. The Fourier amplitude spectra of the ground acceleration reveals that the maximum energy is carried by the low frequency (1–3 Hz), part of the seismic waves. The largest response spectra at Alexandria city is within this frequency band. The computed ground accelerations due to strong earthquakes in the Hellenic Arc, Red Sea and Gulf of Aqaba are very small (less than 10 cm/sec^2) although with long duration (up to 3 minutes).

Key words: Alexandria, Egypt, seismicity, modeling, seismic hazard.

Introduction

Alexandria represents the second largest city in Egypt. Historically, parts (Menouthis and Herakleion) of this city were completely destroyed and sunk in the Aboukir Bay under 6–8 meters of water (Fig. 1). The source and the date of destruction are not exactly known, however it most likely took place in the 7th or 8th century (as indicated by excavated coins and jewelries) by either land subsidence (Geotimes, 2000) or earthquakes (Stanford Report, 2000).

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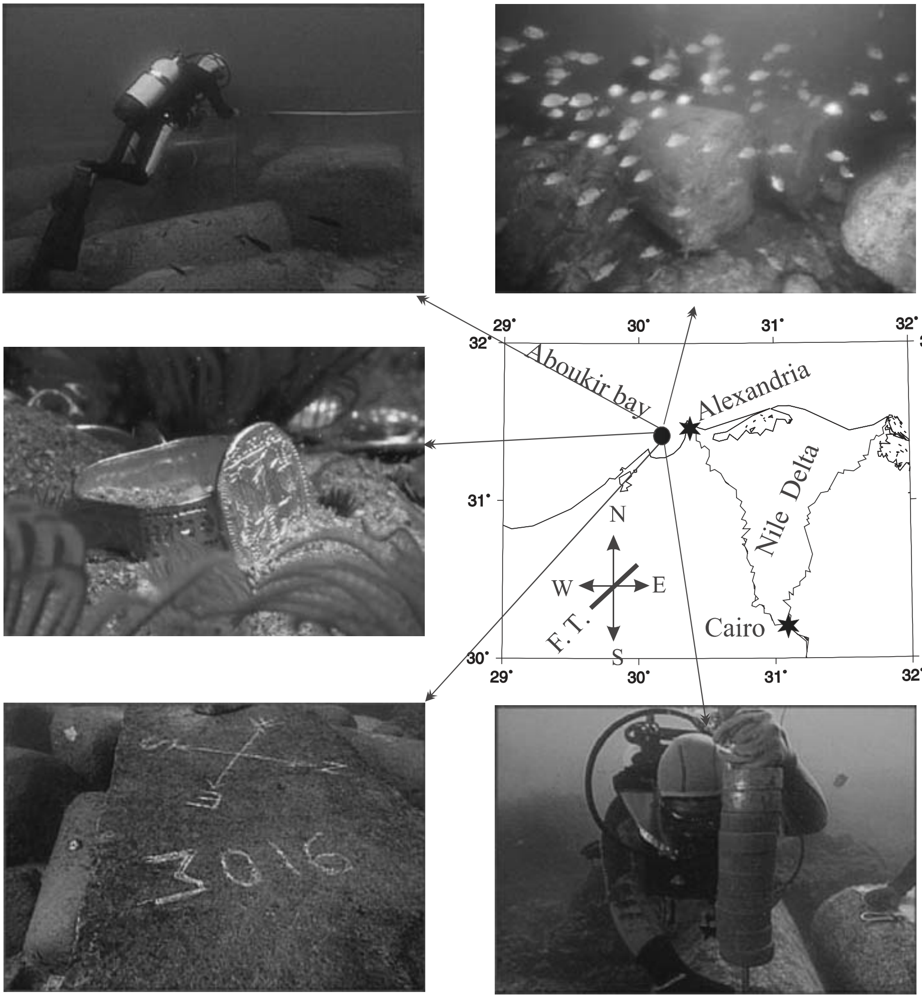

Figure 1
Examples of the archeological remain discovered in Aboukir Bay (solid circle) off Alexandria (solid star). All of the destroyed columns are collapsing (F.T) in the NE-SW direction.

The city was also shaken by five earthquakes in the last century. The most recent one occurred on May 28, 1998 (Fig. 2). This event had a moderate magnitude (m_b = 5.5 and $Mo = 2.0 \times 10^{24}$ dyne cm) and was located at about 250 km northwest of Alexandria (27.64°E and 31.45°N), It was felt with intensity II as far as Nicosia and Aqaba and injured one person in Cairo. Seismic stations in the surrounding areas recorded no activity before or after the mainshock.

Generally speaking, the Alexandria offshore area has low to moderate seismicity (Fig. 2(a & b)) however, regions like Hellenic Arc, Red Sea and Gulf of Aqaba which

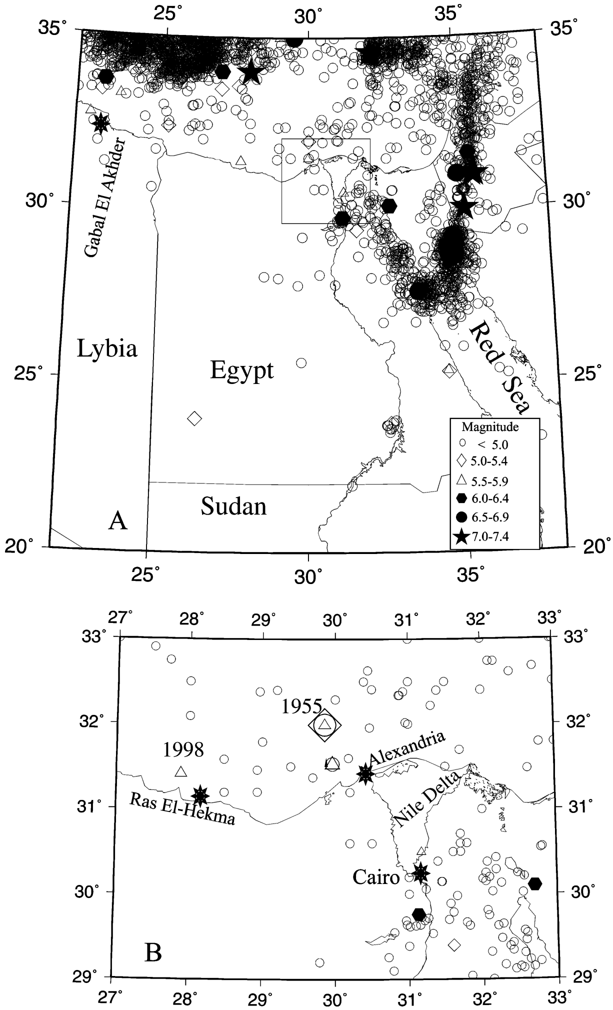

Figure 2
Distribution of earthquake epicenters in the vicinity of: (A) Egypt and (B) Alexandria (square area in A) within the time period 1900–2000. Star represents the destructive events. (★) denotes, the sites location.

are about 400–600 km from the city have high seismicity (Fig. 2a) and the impact on the city is sometime enormous (Maamoun *et al.*, 1984; Kebeasy, 1990; Ambraseys *et al.*, 1994).

The main objectives of this research work are to: (1) review the tectonic and seismic history in the site of Alexandria and its surrounding, (2) obtain the source parameters of the 1998 earthquake in an attempt to understand the tectonic behavior of the offshore area, and (3) estimate the level of seismic hazard expected from future strong earthquakes.

Tectonic Setting

The primary features of active plate tectonics in the vicinity of Egypt have been discussed in detail by many authors (McKenzie, 1970, 1972; Neev, 1975; Ben-Menahem *et al.*, 1976; Garfunkel and Bartov, 1977; Ben-Avraham, 1978; Sestini, 1984; Mesherf, 1990). Egypt is located near three major plate boundaries, namely: the African-Eurasian margin (including the Hellenic Arc), Gulf of Aqaba-Dead Sea (the Levant transforms) fault and the Red Sea margin (Fig. 3a). The Sinai block or subplate is partially separated from the African plate by spread-apart or rifting along the Gulf of Suez (Woodward-Clyde Consultants, 1985). In addition to these plate boundaries there is a megashear zone running from southern Turkey to Egypt (Neev, 1975; Kebeasy, 1990) marked by relatively moderate and scattered seismicity.

The Alexandria offshore is located within the Afro-Arabic Platform block which is contiguous with southern Alpine overthrust belt (Orwig, 1982). The contact between these blocks is traceable on seismic profiles from exposed areas in Syria and eastern Turkey into deep water south of the islands of Crete and Cyprus. This Afro-Arabic platform block is subdivided into four different units (Orwig, 1982; Said, 1990), which is also affected by a major fault known as the Suez-Cairo-Alexandria fault zone. This fault is characterized by a low to moderate seismic activity in Egypt. The event of October 1992 more likely occurred along one segment of this fault system.

On the other hand, the city of Alexandria itself is a part of the Nile Delta cone (Fig. 3b), which is considered as a large hinge zone that consists of several southward half-grabens. These grabens are deformed and bounded by east-west-oriented northward-dipping listric faults (Hussein and Abd-allah, 2001). Two mechanisms are suggested for the deformation of the Nile Delta hinge zone. The first one is related to the late Oligocene-Early Miocene compression cycle, in the direction NW-SE to NNW-SSE, that resulted from the Alpine Orogeny (end of the Eocene). This compression reactivated the E-W orientated deep-seated Mesozoic faults. The second mechanism is related to northward gravitational sliding of Oligocene-Pliocene shale and sandstone over the pre-Eocene carbonates rocks. Both mechanisms acted together during the deformation of the Nile Delta hinge zone (Hussein and Abd-allah, 2001). In general, these mechanisms create a complicated tectonic setting in the site of Alexandria and its vicinity (Fig. 3b).

Seismicity Review

Alexandria city has experienced about 25 damaging earthquakes spanning the time period 320 to 2000 (Maamoun *et al.*, 1984; Ambraseys *et al.*, 1994; El-Sayed *et al.*, 2000). Nine of these earthquakes are located offshore of Alexandria. The magnitudes of these local earthquakes are moderate ($M_s = 6.7$), nonetheless they

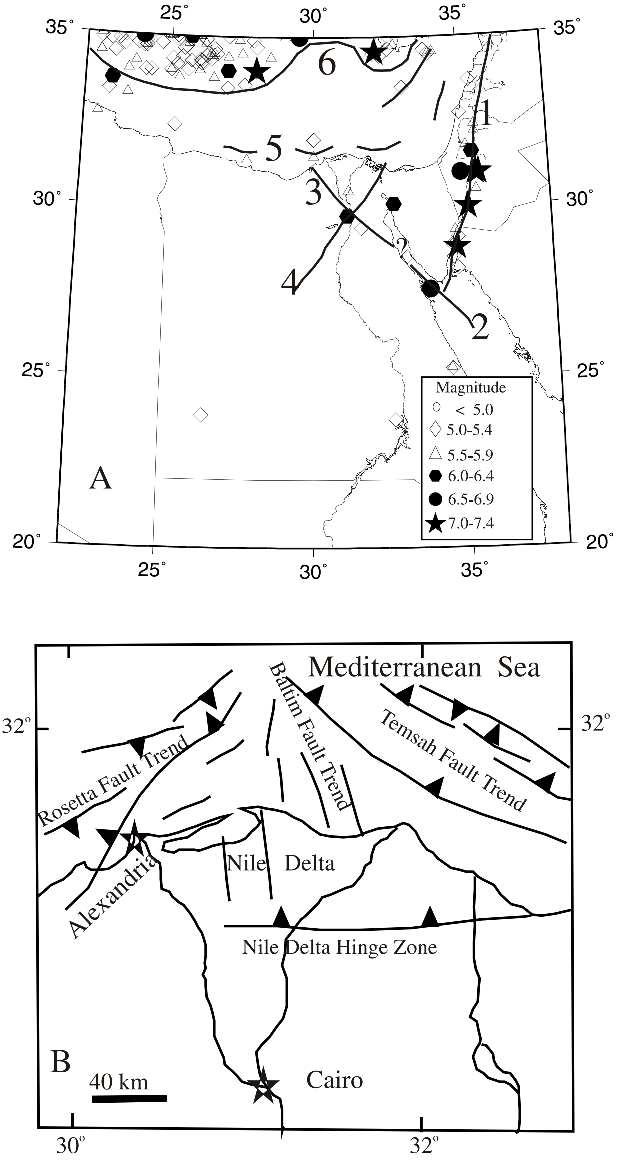

Figure 3

(A) The distribution of earthquake epicenters (with magnitude > 5.0 in time period 1900–2000) and the major tectonic elements in the vicinity of Egypt (modified from Sestini, 1984; Kebeasy, 1990; Mesherf, 1990). (B) Local tectonic elements in the vicinity of Alexandria (modified from Hussein and Abd-allah, 2001). (1) Denote the Gulf of Aqaba-Dead Sea, (2) Red Sea, (3) Suez-Cairo-Alexandria fault zone, (4) Eastern-Mediterranean-Cairo-Faiyoum fault zone, (5) Egyptian Coastal zone and (6) Eastern-Mediterranean (Hellenic Arc).

were felt with intensities reaching IX, MSK (AMBRASEYS *et al.*, 1994). The event of 1955 (M_s = 6.7) is the most recent locally damaging earthquake. During this earthquake a few people were injured. A considerable number of adobe house were destroyed and a few of those with concrete construction suffered damage (MAAMOUN *et al.*, 1984; AMBRASEYS *et al.*, 1994). In general, the duration of shaking in Alexandria from such offshore earthquakes did not exceed a few (2–3) seconds (AMBRASEYS *et al.*, 1994).

The other 14 earthquakes were located mainly in the Eastern Mediterranean region (i.e., Hellenic Arc). These earthquakes have relatively large magnitudes, M_s = 7.8, (AMBRASEYS *et al.*, 1994). The observed intensity from such remote earthquakes in Alexandria extends to VI. According to AMBRASEYS *et al.* (1994), these remote earthquakes were generally felt in Alexandria for about 3 minutes or more. The most severe damage in Alexandria was related to events located in the Eastern Mediterranean (Ambraseys *et al.*, 1994). Some of these quakes (e.g., the event of 320) triggered a destructive tsunami that destroyed more than 50,000 houses (one third of the city) and killed 5,000 people in Alexandria.

Historical and recent reports indicated that the events which are located as far as the Red Sea and Gulf of Aqaba are felt in Alexandria but without damage. The recent examples of 1969 (M_s = 6.9) and 1995 (M_s = 7.3) in the northern Red Sea and Gulf of Aqaba, respectively, were felt in Alexandria with intensity (III–IV) but caused no damage. Unfortunately, the reported intensity data for Alexandria are insufficient to study their return periods.

The Effects of 1998 Earthquake

On May 28, 1998 a moderate (m_b = 5.5, Mo = 2.0×10^{24} dyne cm) earthquake occurred approximately 250 km northwest of Alexandria (27.64°E and 31.45°N). Immediately after the May 28, 1998 earthquake, 55 locations in the northern part of Egypt were surveyed to collect observations and reports of the shaking effects on buildings, ground and or people (HASSOUP and TEALAB, 2000). Based on this survey, maximum intensity (VII) was assigned at Ras El-Hekma village (~300 km west of Alexandria) on the Mediterranean Sea coast (Fig. 2b). The ground fissures trending NW-SE were observed along the beach. These fissures were observed only in those areas of unconsolidated sedimentary deposits. In terms of damage some cracks were observed in concrete buildings. On the other hand, in Alexandria there were no reports of damage. Some people left their houses; the windows rattled and hanging objects swung, but the direction of the ground motion was poorly identified. HASSOUP and TEALAB (2000) assigned an intensity V-VI in Alexandria city.

According to ISC reports, the event of 1998 was felt even as far as Nicosia (intensity = II) and Aqaba, causing one injury to a person in Cairo city. It is very important to mention that there was no seismic activity before or after the mainshock.

Modeling of 1998 Earthquake

The event of 1998 has triggered a considerable number of seismic stations worldwide. In modeling study, stations located within the distance range 30° – 90° were considered. For closer stations (< 30°) the upper mantle structure creates arrivals that do not belong to the source, while for distant stations (> 90°) the core arrivals started to influence the seismograms (CIPAR, 1980). To obtain the best data quality, only seismograms recorded by the digital network of Incorporated Research Institute for Seismology (IRIS) were used.

Altogether, twelve broadband body wave records (*P* and *SH*) were used. The choice of these records is mainly based on the signal-to-noise ratio. The available stations cover a relatively good azimuthal range, excepting the SW quarter of the sphere.

As the selected stations are located in different geological settings, a simplified average model proposed by Jeffreys-Bullen is adopted. According to this model the crust consists of two layers with thicknesses 15 and 18 km and *P*-wave velocities 5.6 and 6.5 km/sec, respectively. The two layers are underlined by a half-space layer with V_p 8.0 km/sec.

P-wave polarities of 14 seismograms were picked up and used to construct the starting focal mechanism in our inversion. This solution shows a reverse faulting mechanism with a constrained northwest nodal plane dipping northeast (Fig. 4).

The observed records were then inverted using the technique of KIKUCHI and KANAMORI (1991) for a single point source until the best fit (between observed and synthetics) was obtained (Fig. 4). The differences between the observed and synthetic records were calculated to obtain the residuals. Using these residual data, iterative inversion was carried out to determine the locations (in space and time) and seismic moments of the subsequent sources. In general, KIKUCHI and KANAMORI's (1991) technique used in the present study is developed to represent large complex sources, however, it is successfully extended to represent the complex events that have moderate magnitude (PINAR and TÜRKELLI, 1997; PINAR and KALAFAT, 1999).

In this study, the Green's functions for the six elementary tensors were calculated for a grid of 45 points separated by 4 km. These points represent a plane (9 in horizontal and 5 in depth) that includes the source area. The calculated Green's functions were convolved with the *Q* filter (1.0 and 4.0 seconds for *P* and *S* waves, respectively) and with source time function of a rise time $\tau_1 = 1.7$ and duration $\tau_2 = 3.4$ seconds. Using the above parameters, the first 60 seconds of the seismograms were simultaneously inverted, allowing the mechanism to change during the rupture to reduce the residuals.

It was not possible to model *SH* phases with a single source; on the other hand, two sources separated by 4 seconds give the best fit (Fig. 4). The suggested sources are located 8 km away from each other on a plane striking NNW-SSE with focal depths 28 and 24 km, respectively. As shown in Figure 4, for all stations, there is a

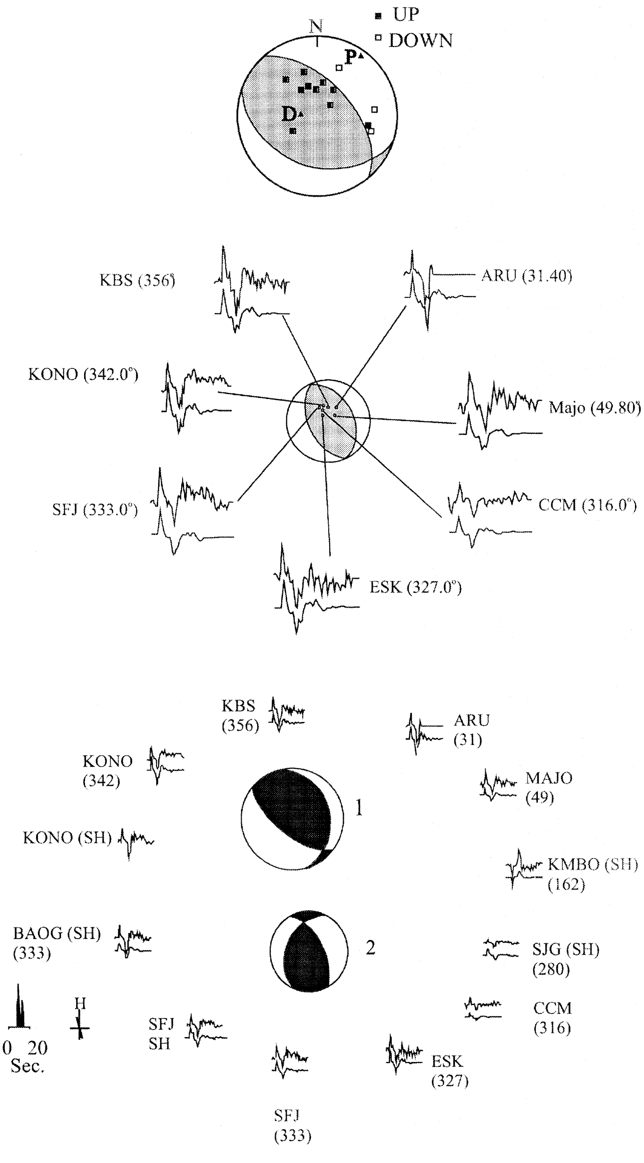

Figure 4
Focal mechanism obtained for the 1998 earthquake from (top) polarity data (middle) inversion of P waveforms and (lower) inversion of *P* and *SH* waveforms. Station name and azimuth (between brackets) are given beside the record. Beach balls 1 and 2 correspond to the first and second subevents, respectively.

relatively good agreement between observed and synthetics, except for the KMBO station which lies close to the nodal plane.

Based on modeling results, the rupture process started with the first subevent (strike = 347°, dip = 29°, slip = 125°) along a fault plane trending NNW-SSE of low dip angle. Four seconds later, the second subevent (strike = 334°, dip = 60°, slip = 60°) coupled the motion to a shallower but steeper plane. The mechanism of the first subevent compares adequately with those of HUSSEIN *et al.* (2001) and the Centroid Moment Tensor (CMT) solution. Generally, the mechanism of the 1998 earthquake is similar to that of the 1955 and 1988 earthquakes (nearby offshore events, ABO-ELENEAN, 1993) in terms of fault type, reverse, but is relatively different in terms of fault trend and strike-slip component.

Seismic Hazard

The seismic hazard scenario for Alexandria and its environs was examined using the deterministic approach developed by COSTA *et al.* (1992, 1993). This method uses the information of earth's structure (crustal models) and level of seismicity (earthquake catalogue, seismogenic zones and focal mechanisms) to compute a synthetic seismogram that could be observed from an expected large earthquake.

The database of earthquake catalogue, seismogenic zones, and focal mechanisms of the identified seismogenic zones prepared by EL-SAYED *et al.* (2001) was used in this study. The obtained focal mechanism from body-wave inversion for the 1998 earthquake is used to describe the source complexity of the offshore area in better way, instead of the 1955 events derived from *P*-wave polarities (EL-SAYED *et al.*, 2001).

The structural models of the media beneath the considered area are represented by a number of flat layers (Fig. 5). The thickness, the density and the *P* and *S* waves of these layers are taken from deep seismic sounding and Bouguer anomaly profiles published by the Egyptian General Petroleum Company (GPC). These data are stored in the Atlas of Geology at Cornell University, USA (BARAZANGI *et al.*, 1996; MAKRIS *et al.*, 1988; EL-SAYED *et al.*, 2001). The *S*-wave velocity is taken as $V_P/1.73$. The quality factors are taken from XIE and MITCHELL (1990).

The geotechnical parameters (for the upper 300 m) in/and around this area have been investigated by many authors (e.g., MARZOUK, 1995; MOHAMMED, 1995; HELAL, 1998) and governmental building organizations (e.g., Educational Building Authority, EBA). These investigations were carried out by using shallow seismic techniques and drilling boreholes. It should be emphasized that the velocities (V_p and V_s) given by different authors are in a good agreement with laboratory measurements made by EBA. Figure 5 summarizes the crustal parameters used in this calculation. Due to a lack of specific models for the upper mantle, a standard continental model of HARKRIDER (1970) and DU *et al.* (1998) has been considered.

When the seismicity, the source mechanisms, the structural models and the observation points are defined, synthetic signals are computed using the modal summation technique (PANZA, 1985; PANZA and SUHADOLC 1987; FLORSCH *et al.*, 1991).

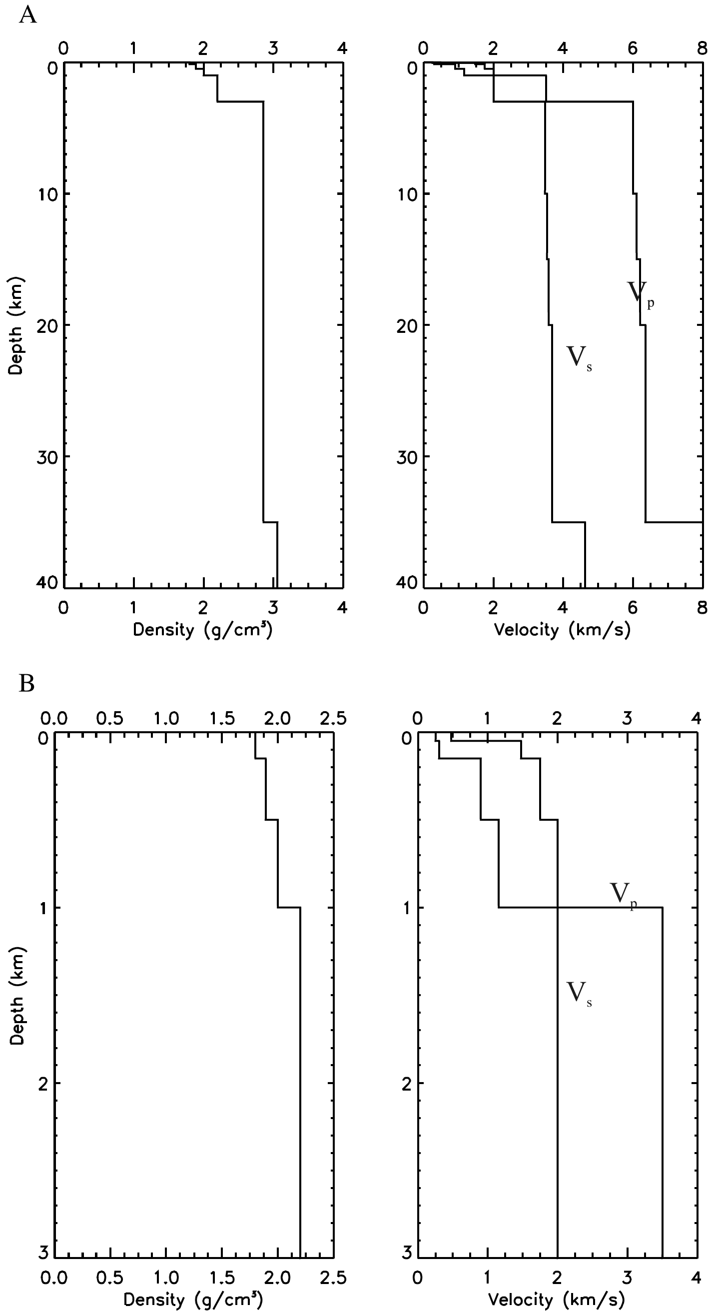

Figure 5
(A) Crustal model considered in this study and (B) zoom of the upper 3 km.

To study the ground motion in the vicinity of Alexandria, roundly 3000 earthquake were used (Fig. 2a). The horizontal *P-SV* (radial) and *SH* (transverse) components of motion were computed and rotated to the common reference system (N-S and E-W directions) after which their vector sum is calculated. The total number of seismograms expected for the above configuration would exceed 90,000. To reduce the computations, the source-receiver distance is kept below 100 km. At each observation point all seismograms generated by different sources are examined and the largest component of ground motion is selected for further analysis. The synthetic signals are computed to obtain the peak ground displacement (DMAX), velocity (VMAX) and acceleration (AMAX) reaching a maximum frequency of 10 Hz (Fig. 6).

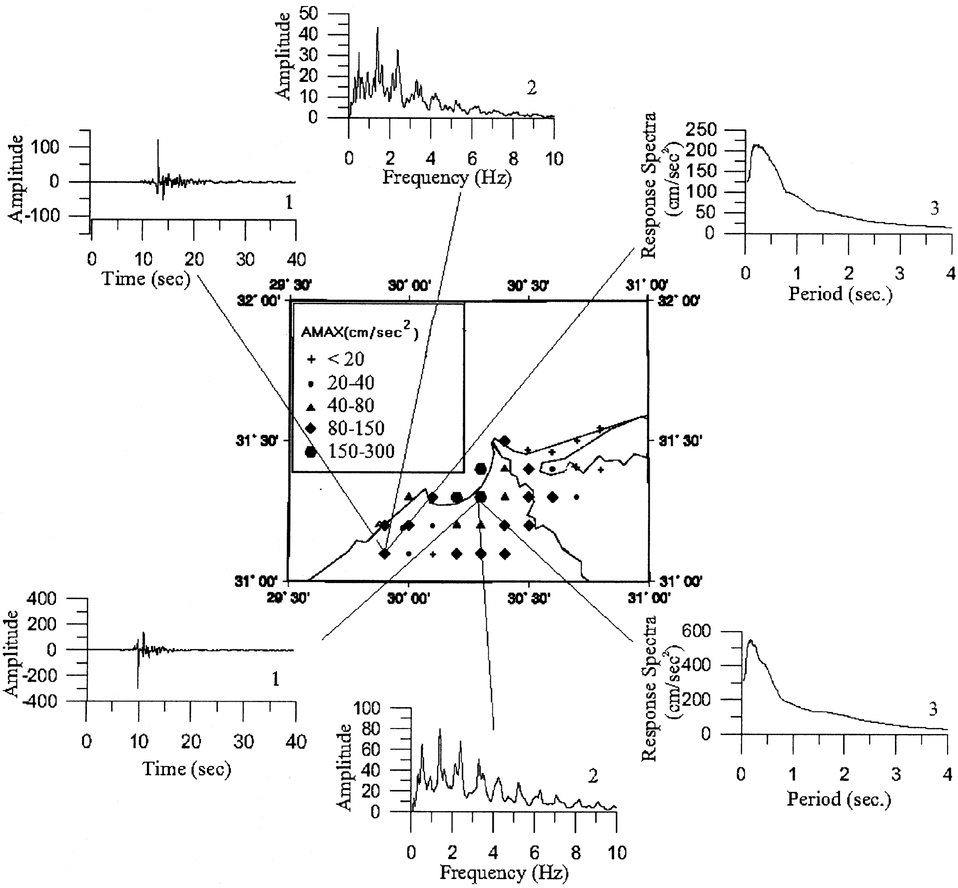

Figure 6
Distribution of the computed peak ground acceleration computed for earthquakes with epicenter distance = 100 km. 1, 2, 3 in the left of the traces refer to the calculated acclerograms, Fourier amplitude spectra and response spectra, respectively. AMAX stands for the maximum computed acceleration amplitude.

To investigate the effects of large, distant earthquakes, calculations were performed for the largest observed earthquakes in the most active zones, e.g., the Hellenic Arc, Gulf of Aqaba, Red Sea (Fig. 7).

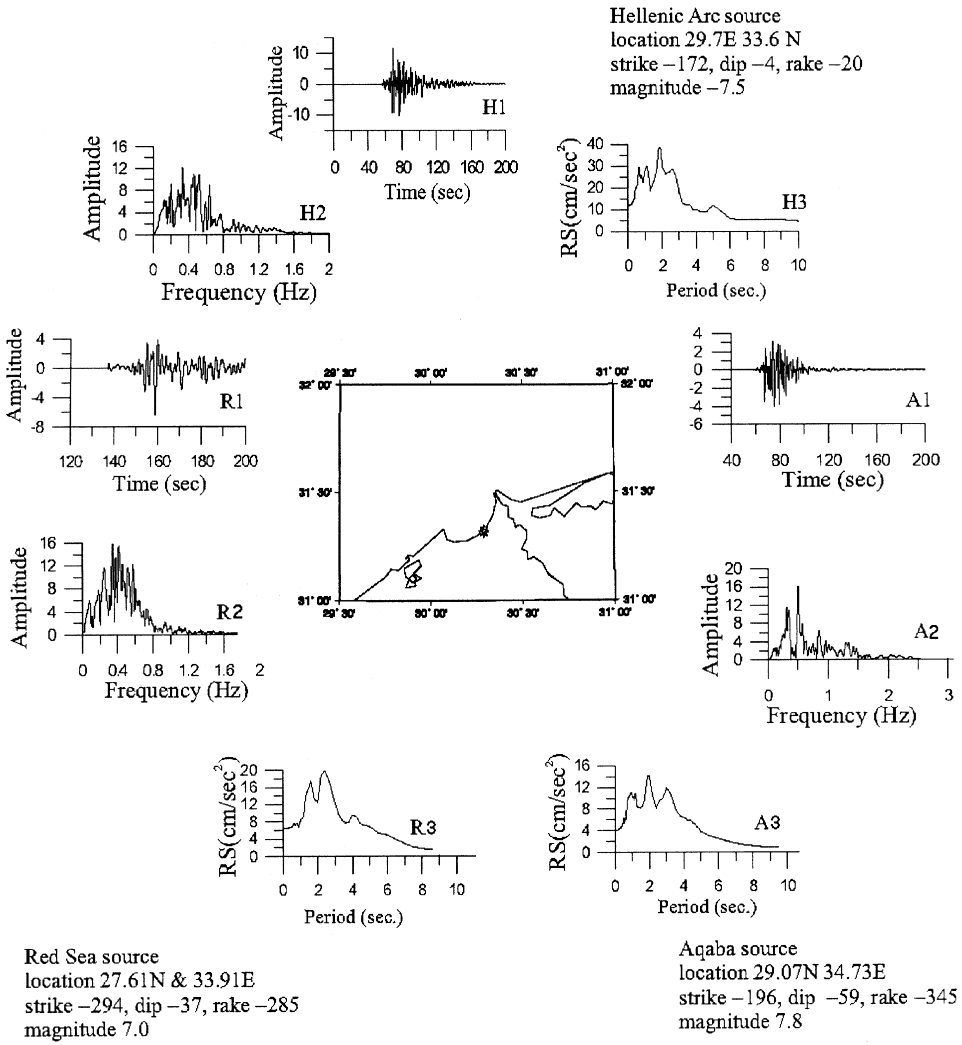

Figure 7
Computed peak ground acceleration at Alexandria using remote earthquakes. A, R, H corresponding to Aqaba, Red Sea and Hellenic Arc, respectively and 1, 2, 3 as in Figure 6. The parameters considered for each source are given in the top and bottom of the Figure. RS stands for response spectra.

Discussion

Alexandria is located approximately 300 to 600 km from three known active plate boundaries, namely: the Red-Sea, the Gulf of Aqaba and the Hellenic Arc (McKenzie 1970, 1972; Sestini, 1984; Mesherf, 1990). The interaction among these three plate boundaries created major fault zones in Egypt as: (1) Eastern-Mediterranean Cairo-Faiyoum fault zone (Neev, 1975; Sestini, 1984; Mesherf, 1990), (2) Suez-Cairo-Alexandria fault zone (Kebeasy, 1990). These fault zones are very close to the city of Alexandria (Fig. 3). Moreover, deep seismic sounding reveals that there are minor faults such as Rosetta fault which trend a few kilometers from Alexandria city (Fig. 3b, Hussein and Abd-allah, 2001).

As a result of this complex tectonic setting many earthquakes occurred in the vicinity of Alexandria, both in recent and historical time (Ambraseys *et al.*, 1994; Maamoun *et al.*, 1984). The spatial distribution of the earthquakes epicenters (Fig. 2) shows that there are areas of very intense (e.g., plate boundaries) and others of low (e.g., offshore area) activities. For those of intense seismicity, there are a considerable number of focal mechanisms that allow us to understand its geodynamic behaviors (McKenzie, 1970; and Rotstein and Kafka, 1982; Sestini, 1984; CMT database). Controversy, the number and quality of the focal mechanisms available for those of low seismic activity (like the Egyptian coastal zone) are not enough to have the clear understanding for the tectonic setting (Sestini, 1984; Kebeasy, 1990; Mesherf 1990).

The modeling of the 1998 earthquake (in the Egyptian coastal zone) reflected the complexity of the tectonic setting in this area. This complexity was generated originally by the interaction between the African and Euro-Asian plates and manifested towards the North African coast (Le Pichon and Sibuet, 1981). It is supported by the polarity mechanisms of the 1955, 1987 and 1988 earthquakes (Abo-Elenean, 1993). Other support is the recorded seismograms at Helwan station for the events of 1955, 1987, 1988 and 1998. *P* waves in these seismograms are not simple but rather complicated and usually include different phases of *P* waves (Hussain *et al.*, 2001).

As a result of this complex stress regime, damaging earthquakes had occurred in the vicinity of Alexandria (Ambraseys *et al.*, 1998; Kebeasy, 1990; Maamoun *et al.*, 1984). Some of these damaging earthquakes are apparently missing. As an example, the damage in Menouthis and Herakleion is more likely caused by an earthquake (which is not known yet). This is supported by: (1) the collapsed columns are falling down in the same direction NE-SW (Fig. 1), (2) the presence of coins and jewelry suggest a sudden collapse, (3) the sharp sand grains in the bottom of Aboukir Bay reflecting active tectonic environment, and (4) the Cairo-Alexandria fault system (NE-SW) is passing by the area and recently generated frequent moderate earthquakes (Geotimes, 2000). This does not exclude the possibilities of land subsidence as suggested in the Stanford Report (2000).

Such phenomena (liquefaction and land subsidence) were observed in the area after the event of 1926 (AMBRASEYS and ADAM, 1998).

As can be seen, the seismic hazard is relatively high in Alexandria. e.g., the area just in front of Alexandria represents a spot of activity that produces frequent moderate (M_s = 6.7) earthquakes (AMBRASEYS *et al.*, 1994). The computed ground motion (displacement DMAX, velocity VMAX and acceleration AMAX), at a distance less than 100 km, are 7.1 cm, 21 cm/sec and 300 cm/sec^2, respectively. These values are slightly higher than the computed values, at 1 Hz, by EL-SAYED *et al.* (2001). The Fourier amplitude spectra show that the energy of the peaks is of low frequencies that have the maximum response from the site (Fig. 6). The total duration of the computed ground motion traces are in the order of a few seconds. The concentration of damage to high buildings and construction that is generally of low frequencies response during the offshore events of 951 and 1955 support the obtained results. Other support is the duration of shaking. These earthquakes were strongly felt for 2–4 seconds (AMBRASEYS *et al.*, 1994), in agreement with the computed values. Unfortunately, there were no stations available in Alexandria to verify our calculation quantitatively but according to PANZA *et al.* (1999) conversion table the values of AMAX correspond to intensity VIII-IX which is in agreement with the one observed during the 1955 earthquake.

Remote events also could have their impact on Alexandria city. As an example, the ground motions due to an earthquakes with magnitude (M_s = 7.5) in the Hellenic, (M_s = 7.0) in the Red Sea or (M_s =7.8) in the Gulf of Aqaba have peaks of 4 cm, 5 cm/sec and 12 cm/sec^2, respectively. These peaks are reported around 1 Hz. Most of the remote earthquakes (e.g., the 320, 557, 1303, 1926 and 1996 events) were felt in Alexandria in the order of minutes (AMBRASEYS *et al.*, 1994; AMBRASEYS and ADAM, 1998; EL-SAYED *et al.*, 2001) as also predicated by our calculations. In general, the computed intensity for remote sources is smaller than the observed one by one-two units. This may be attributed to local site effects that are not taken into account in our model. The coupling between the long duration of shaking and the unconsolidated water-saturated soft sediments may cause liquefaction and thus increase the level of risk. It should be also emphasized that liquefaction phenomena were associated with the events of 1926 and 1998 (AMBRASEYS *et al.*, 1998; HASSOUP and TEALAB, 2001). In addition to the seismic risk, strong remote events had triggered a strong tsunami (e.g., the events of 320 and 1303) that caused severe damage to Alexandria (AMBRASEYS *et al.*, 1994; EL-SAYED *et al.*, 2001). The strongest tsunami is reported in 320. In Alexandria the sea water passed beyond its boundaries and flooded a vast amount of land, so that on retreat of the water the sea skiffs were found lodged on the roofs of many houses. In Alexandria, 50,000 houses were flooded and 5,000 people were drowned. Ships were carried by the waves over the city walls (AMBRASEYS *et al.*, 1994).

Conclusions

From this study we can draw the following conclusion:

1. Alexandria city is located in the vicinity of three plate boundaries that interact with each other generating a complex system of major and local faults close to Alexandria offshore. These faults are associated with small to moderate earthquakes. The focal mechanisms and the waveforms of the offshore events reflect the complexity of this tectonic zone. As a result of this complexity, it was very difficult to represent the moderate earthquake of 1998 by one source and fit both *P* and *SH* waves.

2. Some of the historical earthquakes information in the vicinity of Alexandria is probably missing. As the under-water archeological remains in Aboukir bay strongly support, the city was destroyed by either local or remote earthquakes.

3. Offshore events have strong and short duration of shaking at Alexandria city. The energies of the main peaks are of low frequencies (less that 4 Hz) that have the maximum response spectra from the site. While those in remote areas have a very long duration of shaking however their peaks are relatively weak. These peaks are also of a very low frequency, which is coherent with the response spectra.

4. Remote earthquakes in the Eastern Mediterranean may also cause liquefaction and/or trigger strong destructive tsunami in Alexandria.

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