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Scenarios of Seismic Risk in the United Arab Emirates, an Approximate Estimate

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Abstract. We estimate the losses due to 10 scenario earthquakes in 150 settlements of the United Arab Emirates (UAE). For southern Iran, we use four source zones and the maximum magnitudes in them as determined by GSHAP ($7.2 \leq M \leq 8.1$). For six local scenario earthquakes, we use the range $5.5 \leq M \leq 6.5$, place the sources mainly on mapped faults and vary the distance to major cities from 10 to 60 km. In the test case of the Masafi earthquake (M5, 11 March 2002), the method and data bank we use yield the correct results, suggesting that our approach to the problem is valid for the UAE. The sources in Iran are expected to cause only minor damage, except for an M8.1 earthquake in the Makran region. For such an event we expect some deaths, several hundred injured and a loss of 3–6% of the value to the building stock in the northeastern UAE, including Oman. The losses for local scenarios with epicenters in the unpopulated areas of the UAE and for scenarios with $M < 5.8$ are estimated to be minor. Because the two major mapped faults run through several of the large cities, scenarios with short epicentral distances from cities have to be considered. Scenarios with M6 near cities lead to estimates of about 1000 ± 500 deaths, and several thousand injured. Most buildings are expected to be damaged to a moderate degree and the loss to buildings is estimated around 1/4 of their value. If the magnitude should reach 6.5, the losses to humans and to building value could be staggering. These estimates are approximate because: (1) there exists no local seismograph network that could map active faults by locating microseismicity; (2) there exist no historically old buildings that could serve as tests for effects due to strong ground motion in the past; (3) there exist no microzonation of the subsurface properties in this region of unconsolidated building ground; (4) there exists no detailed inventory of building fragility. Nevertheless, our conclusion that there exists a substantial seismic risk in the UAE is reliable, because our method yields accurate results in the cases of earthquakes with known losses during the last several decades in the Middle East.

1. Introduction

The United Arab Emirates (UAE) are not as safe from earthquake disasters as often assumed. The magnitude 5 earthquake of 11 March 2002 in Masafi demonstrated that sizable earthquakes can occur in the UAE. This event leads to the question of what might be the maximum likely magnitude for an earthquake in this area. Large earthquakes ($M > 7$) usually occur only in areas with surface expressions of active faults, and relatively active micro-seismicity, although exceptions exist. The

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rupture dimensions of earthquakes in the range $5.8 < M < 6.8$ are small enough, so that they may not generate a surface rupture. Therefore, they do occur where no surface faults have been mapped and many examples are known from areas that had not produced earthquakes before. This leads to the conclusion that an $M = 6.5 \pm 0.5$ earthquake cannot be excluded for the UAE, although the probability of such an event is low. Based on similar arguments, scenarios for earthquakes with magnitudes up to M7 have been constructed for New York city, where the seismicity is also low (Jacob, 1999).

The probability of a large to great earthquake in southern Iran, however, is substantial (Tavakoli and Ghafory-Ashtiany, 1999). The proximity of the UAE to the Zagros and the Makran earthquake belts in southern Iran has led the international working group that assembled the world-map for seismic hazard (Grunthal *et al.*, 1999) to expect ground accelerations in the range of 0.16 to 0.3 g, in the UAE. This places the UAE into the same class as many parts of Iran and Turkey, as well as California. It is therefore clear that damage in the UAE must be expected, due to earthquakes in southern Iran.

The assumption that the seismic hazard is stationary with time holds well, if long periods are considered. Therefore, seismologists agree that future seismic activity can be estimated reasonably well in countries with long histories. For example, in South American countries the effect of earthquakes on colonial stone and adobe buildings has been recorded over centuries, since the conquest by the Spanish. In the UAE, major cities and large buildings are a relatively new development, and thus there are no records of the effects of historic earthquakes in this area. Also, the seismic risk in the UAE is rapidly increasing because of the accelerated urban development. In 1968, few buildings existed in Dubai, which has now a population estimated at one million.

Given the recent M5 earthquake in the UAE and the high probability of large earthquakes in southern Iran, it is timely to estimate the probable consequences of similar or larger earthquakes in the UAE, such that preparations can be made for a possible disaster. Our approach is to estimate the number of deaths and injuries, as well as the extent of the damage for scenario earthquakes. A scenario earthquake is one that could reasonably happen at any time. The size and position of scenario earthquakes is highly uncertain in the UAE because very little information is available on microseismicity, due to the lack of a local seismograph network. Our strategy is therefore to select several likely positions for epicenters, near and far from large cities, and to calculate the effects for a range of plausible magnitudes. This gives a picture of the range of earthquake disasters that could befall the UAE.

2. Method

The locations and sizes of several possible earthquakes are assumed, based on the earthquake history of the area and the current understanding of the regional tectonics. The strong ground motion is then calculated by the program QUAKELOSS

(Larionov *et al.*, 2000) as a function of distance, using the attenuation curve of Shebalin (1968). The data set for the approximate number of inhabitants and buildings in towns of the UAE is then used to calculate the expected damage to and collapse of buildings and the likely number of injured people (Shojgu *et al.*, 1992).

The best estimate for the number of injured and killed people could be obtained if the population number, their distribution in different categories of buildings and the characteristics of each building were known accurately. Because this detailed information does not exist for most cities, approximations are necessary. The information on which the calculations in this paper are based is the number of people in each settlement, as published in consensus reports, and the building types, as well as their distribution in classes, in prototype cities. The database contains a number of prototype cities to cover parts of the globe with similar characteristics with respect to fragility of buildings. In all settlements, the buildings are classified into five fragility classes. The distribution of buildings into these classes in each settlement is derived from the prototype city, but adjusted according to (a) the number of inhabitants, (b) estimates of the degree of industrial development, and (c) the cultural profile. With this distribution estimated, and the number of inhabitants known from consensus figures, the casualties resulting due to the calculated local intensities of shaking is finally computed.

The average fragility of buildings in the major cities that results from this process is different than that in other towns, because they are more industrialized and modern buildings of good quality construction dominate. On average the buildings in the larger cities are assumed to be more resistant to strong shaking than buildings in a small settlement.

In recent years, there have been several publications on earthquake loss estimate and seismic risk in different parts of the world (e.g., in *Natural Hazards* papers by Yong (2001, 2002), Chen (1997), Cha (1998), Balassanian (1998), and Kijko *et al.* (2002)). However, the researchers are not aware of such studies for the UAE, the subject matter of the current research paper.

For calculating ground accelerations, the earthquake is modeled as a point source, located at the assumed epicenter from which the energy flows according to the attenuation curves of Shebalin (1968). Because this model is too simple for long ruptures, the stronger accelerations in directions along the fault, compared to those in directions perpendicular to it, are generated by modifying the attenuation law as a function of azimuth with respect to the fault trace. Along the fault, the attenuation is reduced, perpendicular to it, it is increased, in such a way that the energy is conserved. This is not a physically satisfactory way to achieve the macroseismically observed destruction pattern, however it approximates the observations well.

The computer code and database QUAKELOSS was calibrated, using all available data on casualties due to earthquakes. Worldwide, the number of test earthquakes is approximately 1000. The calibration was done regionally. Regions are defined as areas in which the properties of buildings and their distribution into classes are similar. Regions may include several neighboring countries, especially

Table I. Parameters of scenario earthquakes in Southern Iran

Source zone[1]	Latitude	Longitude	M^1_{max}
1	25.7	58.0	8.1
11	27.7	56.4	7.6
12	27.0	56.0	7.2
13	26.6	55.5	7.0

[1] Tavakoli and Ghafory-Ashtiany, 1999.

if they are small. On the other hand large countries, like Russia, may be divided into sub-regions. For the area of Turkey and Iran, the calibration resulted in accurate estimates of casualties due to past earthquakes (Wyss *et al.*, 2003).

Local amplification of strong ground motion, due to unfavorable soil conditions, may play an important role in future earthquakes in the UAE. The best known example of this phenomenon is Mexico City, in which numerous buildings collapsed due to an earthquake at 300 km distance, whereas buildings located at 50–100 km suffered no or only minor damage. In the UAE, many buildings are constructed on layers of unconsolidated material over more consolidated layers. This is precisely the type of condition that can give rise to amplification of strong shaking. In order to discover the local soil conditions, many cities in earthquake prone areas apply microzonation for seismic risk evaluations. That is, the soil conditions are mapped on a scale of city blocks. In the cities of the UAE, microzonation has not been done. Therefore, the amount of possible local amplification of strong ground shaking is unknown, and is not yet taken into consideration in the estimates presented here.

3. Scenarios for Possible Earthquakes

In estimating parameters for scenario earthquakes in southern Iran, we follow Tavakoli and Ghafory-Ashtiany (1999). Their source zones 1, 11, 12 and 13 are closest to the UAE. We accept their estimate for the maximum magnitudes of earthquakes to be expected and assume an epicenter located on mapped faults within these source zones and positioned closest to the UAE. The epicenters and magnitudes we used are listed in Table I. In all cases, the hypocentral depth is selected to be 20 km. Changing the depths does not influence the effects in the UAE because of the considerable distance.

The occurrence time of earthquakes is an important factor to estimate the death number. Therefore, the occurrence time contributes to the uncertainty of the results. In this study, the effects in all scenarios (except Masafi M5) are calculated for a time of 3AM. This is the worst case, because most people are indoors. At the most favorable time, when many people are out of doors, the number of injuries is estimated to be lower by 20%.

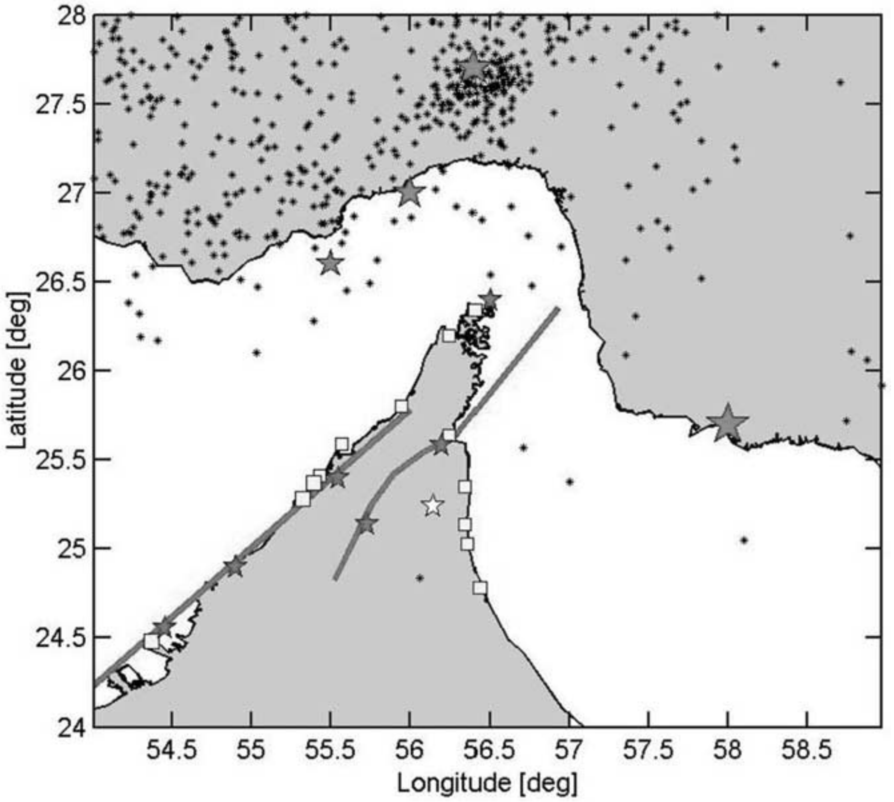

Figure 1. Epicenter map (PDE data) for the UAE and southern Iran. Solid stars mark epicenters of scenario earthquakes (Tables I, II), with their size proportional to proposed magnitudes. Squares show locations of major cities. Solid lines mark faults. The white star marks the M5, 2002, epicenter.

In the UAE the seismicity is monitored by the worldwide network only, which resolves earthquakes with a completeness level of approximately M4.5 in southern Iran. At this resolution level, the UAE show almost no earthquakes (Figure 1). However, on 11 March 2002, an M5 earthquake occurred at 25.24°N/56.15°E (Figure 1). Its hypocentral depth was 10 km. Since that time, numerous small earthquakes were felt locally, but none of them were reported in the worldwide databases.

Two tectonic faults are shown in the area of the UAE on the tectonic map of the Arabian Peninsula (Johnson, 1998). One of them defines the western coastline, running from Abu Dhabi through Dubai and Sharjah to Al Khaimah (Figure 1). The other enters land near the southern border of Oman, coming from the north, and runs southward to the center of the peninsula. Both of these are strike-slip faults. The western fault is left-lateral, the eastern right-lateral. This means that they would accommodate movement of the peninsula to the north, if they were active. Because there exists no local seismograph network in the UAE microseismicity

Table II. Parameters of scenario earthquakes in the UAE

Source zone	Lat.	Long.	M	Hour
Masafi (11/3/2002)	25.24	56.15	5	13
Masafi (scenario)	25.24	56.15	$5.5 < M < 6.5$	3
Dibba	25.55	56.21	$5.5 < M < 6.5$	3
Kumzar	26.4	56.5	$5.5 < M < 6.5$	3
Dubai	25.51	55.53	$5.5 < M < 6.2$	3
Coastal fault	24.9	54.9	$5.5 < M < 6.5$	3
Abu Dhabi	24.68	54.60	$5.5 < M < 6.2$	3
Center UAE	25.14	55.73	$5.5 < M < 6.5$	3

cannot be mapped and consequently we do not know, whether or not these faults are active. In the absence of information on microearthquakes, one has to assume that these faults might be likely locations for future earthquakes.

The 2002 Masafi earthquake was, however, not located on either of these mapped faults (Figure 1). In addition, it was a normal fault with a fault plane striking N59°E and dipping 59° (Harvard catalog). This sense of motion is different than that of the mapped faults, but it would fit into the stress field around a strike-slip fault with a bend, like the Dibba fault.

Because of lack of clear tectonic information, we have to make assumptions. (1) We calculate the effects for a range of magnitudes $5 > M > 6.5$. (2) We select some of the hypothetical epicenters on the mapped faults, although the Masafi earthquake shows that sizable earthquakes can happen off the faults. (3) We select two types of locations, far from major cities and close to them. The distance to the large cities is a critical parameter. If a hypocenter should be located exactly beneath a major city of the UAE, the disaster would be enormous. We do not present such a scenario because this coincidence is not very likely.

In all scenarios for sources within the UAE, the hypocentral depth is assumed to be 10 km. Changing the depths strongly influences the effects in cities near the assumed epicenter. The depth we selected for the relatively moderate magnitudes in our scenarios are the most reasonable ones, given depths distributions of earthquakes in areas where this parameter is well known.

The Masafi earthquake of M5 (2002) is a model for constructing scenario earthquakes, and we use it to test the performance of our method. For the range of magnitudes, we select $5.6 > M < 6.5$, for the reasons given in the introduction. The parameters for the scenario earthquakes in the UAE are given in Table II and their epicenters are shown in Figure 1.

Table III. Expected losses due to the Masafi earthquake and a repeat with larger magnitudes

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Fujairah)	Damage degree (0–5) (Fujairah)	Economic loss % (Fujairah)
5	0–1	3–9	0	0	0
5.5	15–38	38–140	0	0	0
5.8	60–140	150–410	5	0.05	0.2
6.0	130–300	310–810	16	0.2	1
6.2	270–570	620–1490	34	0.5	2
6.4	490–1050	1150–2740	55	0.8	6
6.5	630–1340	1460–3490	62	1.0	8

4. Results

4.1. MASAFI SCENARIO AND TEST (TABLE II)

First, we calculate the consequences of the Masafi earthquake itself and compare them to the observed losses. This can serve as an approximate test for the validity of our method in the UAE. Then we estimate the effects of a repeat event, selecting a range of larger magnitudes. It is common that similar size or larger events follow in the vicinity of major earthquakes within months to decades. For that reason, the Masafi scenario is the most plausible one.

The results for the Masafi earthquake of 11 March 2002, using the epicenter, depth and magnitude given by the NEIC, is shown in the first row of Table III. The format of this and the following tables is the same. The second and third columns contain the range of deaths and injuries estimated as a total, for the region affected. The range of these values shown in the Tables is obtained as that containing 90% of the calculated answers, given an assumed error scheme (Larionov, 1999; Shakhramanjyan *et al.*, 2001; Shojgu *et al.*, 1992). The fourth, fifth and sixth columns give the percent of damaged buildings, the average degree of damage (measured on a scale from 0 to 5), and the economic loss to buildings in percent of the value of these buildings, respectively. The information in these three latter columns applies to the largest nearby city (Fujairah in the case of the Masafi earthquake) because these values are more informative than the average, including small towns, would be.

As one sees in row one of Table III the QUAKELOSS-program expects no, or at most one, person to die, and calculates that possibly very few people might be injured. Further, it estimates that buildings in Fujairah would not be measurably damaged. This result agrees with the observations after this earthquake in March 2002, and therefore we have one piece of evidence that supports the applicability of our method to calculate losses due to earthquakes in the UAE.

Table IV. Expected losses due to scenario Dibba

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Dibba)	Damage degree (0–5) (Dibba)	Economic loss % (Dibba)
5.5	17–50	60–300	48	0.7	5
6.0	280–700	680–2500	86	1.9	23
6.2	770–1790	1620–5040	94	2.4	37
6.5	2510–5280	5380–11140	99	3.4	62

The loss estimates for a repeat of the Masafi earthquake with a larger magnitude, and during the night, show that up to M5.8 the disaster would be relatively minor, with fewer than 400 casualties (deaths + injured). Up to and including M6, the expected casualties are below 1000, on average. However, with larger magnitudes the casualties could number several thousand (Table III).

The degree of damage to buildings in Fujairah is estimated as below and up to minor (less than 1 on a scale from 0 to 5) for all magnitudes considered in the Masafi scenario (Table III). Nevertheless, the fraction of buildings affected could reach approximately one third to one half in the upper magnitude range (Table III). The economic loss to buildings is estimated to range between a few to several percent, depending on the magnitude (Table III).

The regional extent of the damage, in case of an M6.5 earthquake near Masafi, is shown as a function of severity in Figure 2. Slight damage is expected to occur to distances of about 60 km, including cities like Al Shinas in the southeast and Al Khaimah in the northwest. Dibba, at a distance of 45 km, is also expected to experience only slight damage with no casualties. Most of the casualties are expected in the epicentral area, along the coast (yellow symbols in Figure 2) and even a few in Fujairah, at a distance of 25 km.

4.2. DIBBA SCENARIO (TABLE II)

This scenario assumes that the Dibba fault (Johnson, 1998) may be active. If we assumed epicentral distances of 40–50 km from Dibba, the results would be approximately those already given in Table III for the Masafi scenario. Because the Dibba fault runs through the city, any distance to the city is possible. For an example of an earthquake close to a major city in western UAE and in Oman, we select arbitrarily an epicentral distance of 10 km to Dibba. At this proximity, about 200 casualties would be expected, with more than half the buildings damaged slightly, and with an economic loss of 5% of the building value, even for an earthquake with the moderate magnitude of 5.5 (Table IV). With increasing magnitude the disaster is estimated to be more severe, reaching proportions that would be very serious for the city at $M \geq 6$.

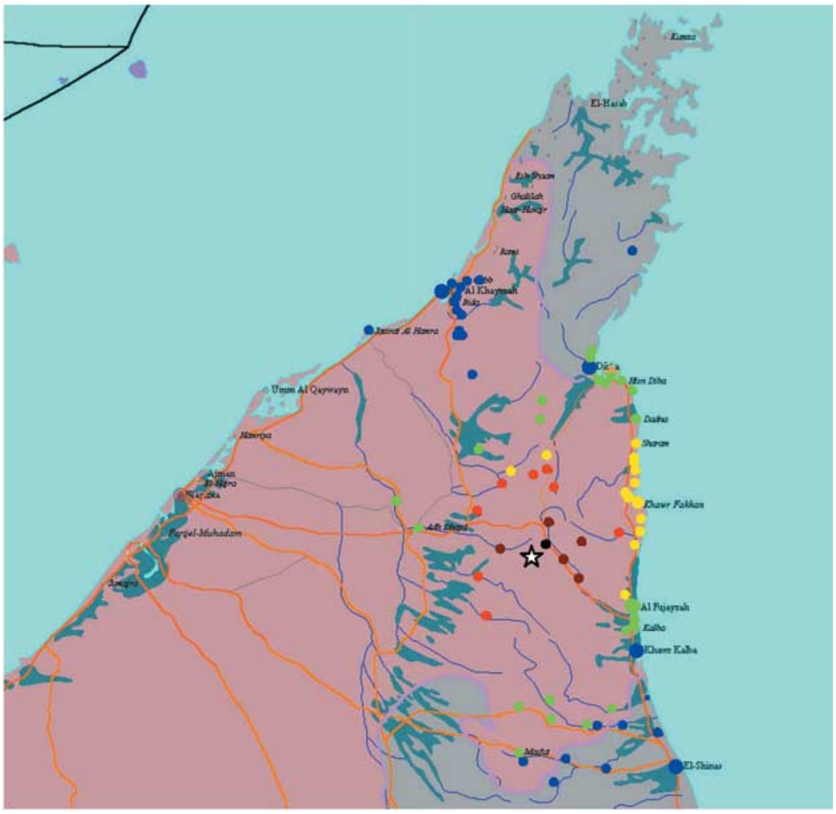

Figure 2. Map of damage due to an M6.5 earthquake at the Masafi epicenter at 10 km depth. The average condition of buildings in each settlement is indicated by a color code. Black – collapsed, red – partially destroyed, yellow – heavy damage, green – moderate damage, blue – minor damage.

4.3. KUMZAR SCENARIO (TABLE II)

This scenario is considered because an earthquake at the northern extent of the peninsula, near the Iranian active zone, seems relatively likely. Because the major city of Al Hasabh is not very populous and because it is located at an epicentral distance of 35 km, the disaster is less severe, in this case (Table V). Nevertheless, the consequences could be serious with $M > 6$.

Most casualties would be expected in Kumzar, and the villages near it. In Kumzar, most buildings are expected to be damaged to a moderate degree for the scenarios with $M \geq 6$.

4.4. COASTAL FAULT SCENARIO (TABLE II)

The fault that defines the west coast (Figure 1) poses a major problem, because it is not known whether or not it is active, and because it runs through the most pop-

Table V. Expected losses due to scenario Kumzar

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Al Hasabh)	Damage degree (0–5) (Al Hasabh)	Economic loss % (Al Hasabh)
5.5	0–4	3–28	0	0	0
6.0	27–75	70–280	5	0.05	0.2
6.5	250–550	560–1400	48	0.7	5

Table VI. Expected losses due to scenario Coastal fault

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Dubai)	Damage degree (0–5) (Dubai)	Economic loss % (Dubai)
6.0	5–12	12–37	0	0	0
6.5	34–70	70–140	4	0.3	0.1

ulated section of the UAE. Thus, it matters a great deal what epicentral distance to the populated 50 km segment containing Dubai, Sharjah, Ajman and Al Quaywayn we select. In the scenario West Fault, we place the hypocenter at the largest distance from major cities (Figure 1). In this way the distances to Dubai and Abu Dhabi are about 60 km. The effects of such a relatively remote event would be minor, even for M6.5 (Table VI).

4.5. DUBAI SCENARIO (TABLE II)

If one assumes that an earthquake of approximately M6 could happen beneath a major city a serious disaster would have to be predicted for most parts of the world. Thus, we do not assume a hypocenter beneath Dubai, but we still need to estimate the extent of the losses if an earthquake in, or near, the most populated segment of the coastal fault should happen. We propose that a reasonable compromise is presented by the epicenter selected for the Dubai scenario, which is located in the least populated part of the 50 km stretch containing the major cities (Figure 1). This epicenter is 33 km from Dubai, thus the losses in Dubai are less than in the other coastal cities.

At that location, an earthquake would cause limited numbers of casualties with M5.5, but with $M \geq 6$, the disaster could be catastrophic (Table VII). The range of values for the damage estimates in Table VII is for the nearest to the farthest. With the selected epicenter, Al Quaywayn is the nearest, Dubai the farthest. However, an earthquake could equally well happen further down the coast, in which case Dubai would be the nearest and Al Quaywayn the farthest.

Table VII. Expected losses due to scenario Dubai

M	Deaths (region)	Injuries (region)	Damaged bldgs % (cities)	Damage degree (0–5) (cities)	Economic loss % (cities)
5.5	24–70	95–470	0–48	0–0.7	0–5
5.8	230–630	690–3040	0–79	0–1.5	0–16
6.0	810–2060	1890–7760	5–90	0.5–2.1	0.2–28
6.2	2020–4900	4500–15720	16–96	0.2–2.6	19–41

Table VIII. Expected losses due to scenario Abu Dhabi

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Abu Dhabi)	Damage degree (0–5) (Abu Dhabi)	Economic loss % (Abu Dhabi)
5.5	0–4	0–7	0	0	0
6.0	7–17	31–140	16	0.2	1
6.2	36–100	150–720	34	0.5	2

4.6. ABU DHABI SCENARIO (TABLE II)

Abu Dhabi is located farthest from the Iranian plate boundary, but the coastal fault runs through it. Therefore we cannot assume that no earthquakes are possible near this city. The epicentral distance we assume is again crucial. The results with an epicenter at 30 km distance (Figure 1) show that the disaster would be limited in this case, up to M6.2 (Table VIII).

4.7. CENTERAL UAE SCENARIO (TABLE II)

It seems of interest to calculate what would happen in case of an earthquake near the center of the UAE. Selecting a point along the Dibba fault near the center (Figure 1), earthquakes with $M \leq 6$ would do little damage (Table IX). An earthquake with M6.5, however, would be capable of minor damage in several of the major cities, and thus the total economic loss in repairs of buildings would be substantial.

4.8. IRANIAN SCENARIOS (TABLE I)

Among the Iranian source zones all but source 1, with its large $M_{max} = 8.1$, are too far from the UAE to cause more than light damage, according to our calculations. The Iranian source 1 scenario is expected to cause considerable losses in the northeast of the UAE (Figure 4), even though the epicentral distance is 150 to 170 km.

Table IX. Expected losses due to scenario Center UAE

M	Deaths (region)	Injuries (region)	Damaged bldgs % (major cities)	Damage degree (0–5) (major cities)	Economic loss % (major cities)
6.0	0–2	4–9	0	0	0
6.5	22–65	100–510	5–20	0.2	1

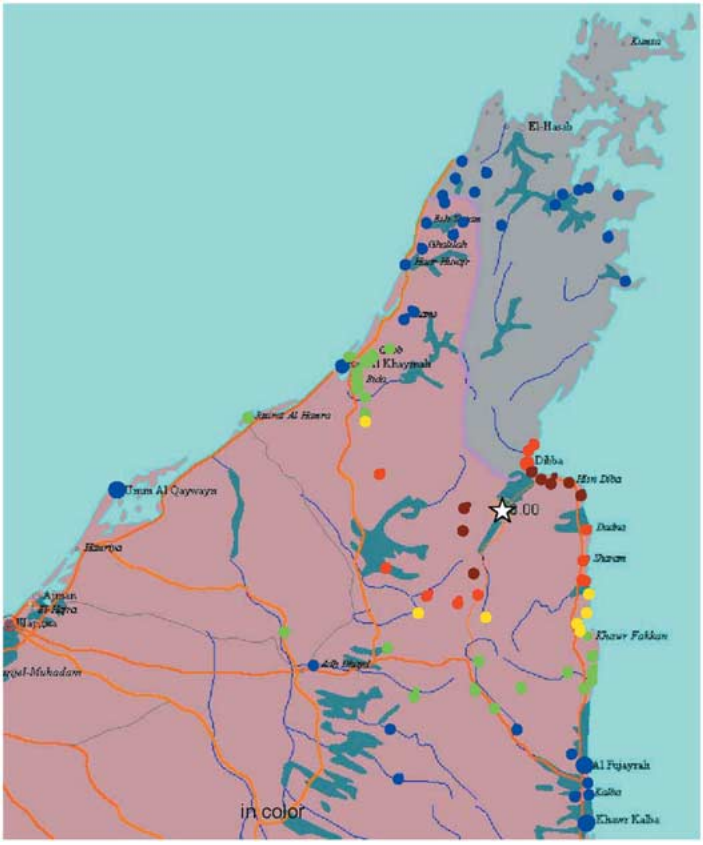

Figure 3. Map of damage due to an M6.5 earthquake on the Dibba fault at 10 km depth and 10 km epicentral distance from Dibba.). The average condition of buildings in each settlement is indicated by the same color code as in Figure 2.

If the magnitude should be smaller, the losses in the UAE are rapidly decreasing (Table X).

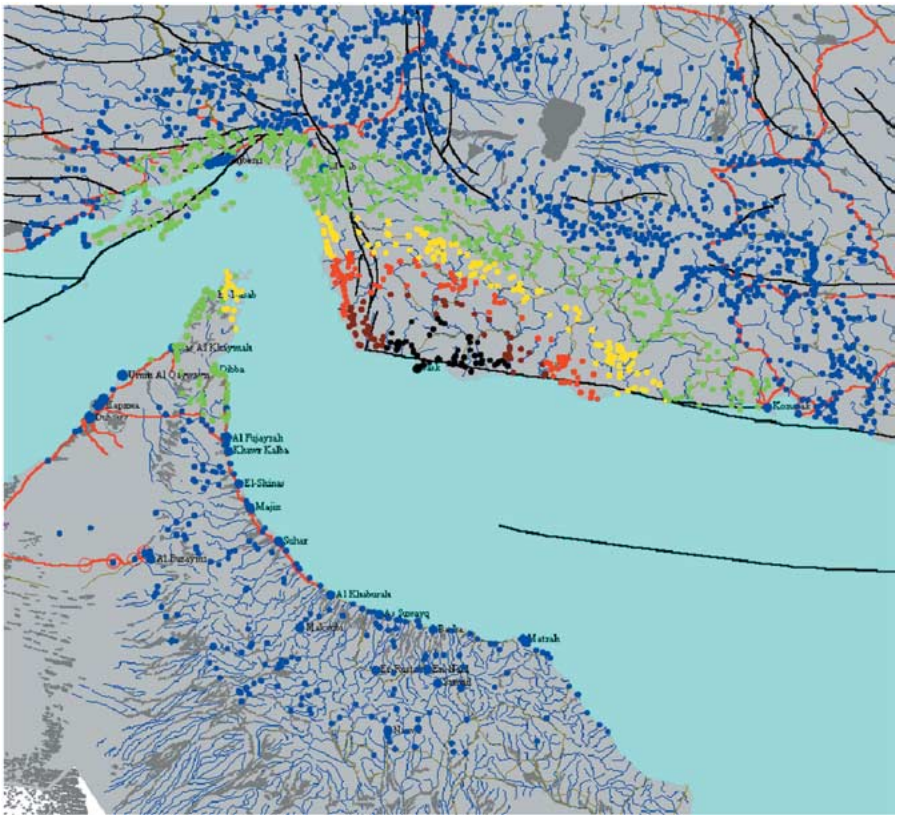

Figure 4. Map of damage due to an M8.1 earthquake on the Makran fault at 20 km depth in Iran (Figure 1). The average condition of buildings in each settlement is indicated by the same color code as in Figure 2.

Table X. Expected losses due to the Makran scenario (Iran, zone 1)

M	Deaths (region)	Injuries (region)	Damaged bldgs % (Dibba/ Al Khasah)	Damage degree (0–5) (Dibba/ Al Khasah)	Economic loss % (Dibba/ Al Khasah)
7.7	~0	~10	8–16	0.1–0.2	0.4–1
7.9	~20	~100	20–30	~0.4	1–2
8.1	~90	~500	40–55	0.6–0.8	3–6

5. Discussion

5.1. GENERAL OBSERVATIONS

The uncertainties in these loss estimates are large because several parameters are poorly known and others have to be assumed. (1) Different sources give different numbers for the population. (2) An inventory of building stock does not exist. The fragility distribution of buildings has to be assumed. (3) Active faults have not been identified because the seismicity is low and there exists no local seismograph network. (4) Tests of building performance in historic earthquakes are practically nonexistent because the history of urban development is short. (5) The amplification properties of the ground on which the buildings have been constructed are not known because no microzonation mapping has been performed, and (6) the occurrence time of earthquakes (in day- or night-time) is unknown.

Our problem is therefore to estimate the order of magnitude of the losses that can reasonably be expected in a region where the seismicity is low, but major earthquakes are possible. Our approach is to construct a range of scenarios that include epicenters as far from cities as possible, and epicenters relatively near cities. For the assumed magnitude, we also select a range, in order to estimate how much the losses vary, as a function of this parameter.

The losses we estimate for given magnitudes of earthquakes are meant to be average values. Our choice of 3 AM as the occurrence time maximizes the casualties, but there is no amplification of ground motions added that must be expected to take place because of the presence of unconsolidated top layers. We assume that these two effects cancel each other, approximately.

5.2. THE TEST CASE

In the single test for the method we have, the Masafi 2002 earthquake, we find that our estimates of the losses agree with the observations. This suggests that the approach we use is approximately correct for the UAE. However, this test is only marginally useful because the magnitude of the earthquake was at the extreme lowest end of events that could cause measurable damage.

5.3. SCENARIOS RESULTING IN NEGLIGIBLE LOSSES

The *Central UAE scenario* (Table II) considers an earthquake as far from cities as possible in the UAE. Consequently, its effect would be minor (Table IX). The losses would also be minor (Table VI) in the *Coastal Fault scenario* (Table II) in which the epicenter was placed at the point of this fault that is at the largest distance from the cities.

For the *Iranian scenarios* in source zones 11, 12 and 13 the ratios of magnitude to distance are such the damage would be minor and few or no casualties would result. To conserve space in this manuscript, we did not present tables or figures for these cases.

5.4. SCENARIOS RESULTING IN SERIOUS LOSSES

Our most realistic scenario is the *Masafi scenario* with $5.5 \leq M \leq 6.5$ (Table II). In our opinion, an M6 earthquake in western UAE would not be a surprising event, whereas an M6.5 would be a surprise, although it cannot be excluded. The casualties (sum of deaths and injured) are expected to remain below 1000, up to M6, and the economic loss to buildings is estimated at 1% of their value (Table III). Several hundred injured and possibly about 200 dead would be a hard hit for the area. In some smaller communities, the percentage of the casualties would be large, which would be a major disaster for these small communities. We estimate that 1% of the building value in Fujairah corresponds to approximately $50 million. We conclude that an M6 earthquake, with epicenter near the 2002 Masafi earthquake, would mean a significant disaster for the eastern UAE. This in spite of the fact that the Masafi epicenter is at a favorable location for minimizing the losses because it is at a maximum distance to the major cities like Fujairah and Dibba.

If the magnitude of a future earthquake in the Masafi area should exceed M6, then the disaster would be major, as can be seen from Table III. The probability of such a large earthquake is small, but the measures to minimize its impact are the same as those necessary to minimize the effects of an M6 event and should therefore be carried out.

The *Kumzar scenario* makes sense because this choice of a possible epicenter is located relatively near the Iranian active seismic zone. Although the transmission of stress away from plate boundaries is not yet understood in detail, there are many examples (Japan, Alaska, Himalayas) in which it is clear that stresses are transmitted to several hundred kilometers. Therefore, an earthquake with the parameters of the Kumzar scenario (Table II) is not unlikely.

We minimized the estimate of losses in the Kumzar scenario, by placing the epicenter at the northernmost tip of the UAE. With a more southern position, the effects on the larger cities would be more significant because of the reduced distance. Thanks to the remoteness of the assumed epicenter the expected losses would be relatively moderate (Table V). A magnitude of M6.5 is realistic in this case, because of the proximity to the plate boundary. In that case, the casualties might exceed 1000 and a 5% loss in building value (amounting to an estimated $100 million) is expected to result.

The Makran scenario would result in extremely serious losses in Iran (Figure 4), but in the UEA the losses would be relatively moderate (Table X). Although the building losses are in the range of 1–3%, summing them up over the many settlements affected (Figure 4), their total may be of a magnitude hard to absorb by the economy in eastern UAE.

5.5. SCENARIOS RESULTING IN VERY SERIOUS LOSSES

A scenario in the eastern UAE with an epicenter closer to a major city than the Masafi epicenter, the *Dibba scenario* (Table II) must be considered as a possibility. Assuming that the Dibba fault may be active, we placed the epicenter for such an event on this fault. The distribution of the resulting damage to buildings is shown for an M6.5 event on the map of Figure 3.

The Dibba scenario shows that a significant to major disaster would result, if an earthquake located on the Dibba fault with M $\geq$ 5.5 struck at a distance of 10 km (Table IV). For an M6 earthquake, for example, the approximate 23% economic loss to building value would amount to \$100 million. The number of deaths would be very large and the number of injured could probably not be handled by the hospitals in the UAE, if the magnitude exceeded M6. The same fate could be expected with equal probability for Fujairah, if an earthquake near it struck. If we constructed a *Fujairah scenario* with epicentral distance and magnitude similar to those in the Dibba scenario then the losses would be larger by the ratio of numbers of inhabitants and buildings in the two cities. That means that for an M6 at 10 km epicentral distance approximately 1000 deaths would have to be expected at Fujairah.

The *Dubai scenario* (Table II) is less likely to occur than the scenarios discussed above, in our opinion. For this reason we chose to use M6.2 as the largest magnitude for which we present the results. We did this because there have been no earthquakes reported in the western UAE. This reduction of the maximum magnitude considered may not be correct because of the following reasons. (a) The coastal fault is straight and over 200 km long. This means it could be capable of very large earthquakes, if it were active. (b) The absence of microearthquakes along major faults producing M8 class earthquakes has been observed in California and Alaska, and is therefore not necessarily a reason to reduce the maximum magnitude considered. Nevertheless we did not present the results for M6.5 in the Dubai scenario because it might be too alarmist a result. However, we think we must consider the results up to M6.2 because of the importance of this urban area to the UAE economy.

If an earthquake should happen within about 35 km of Dubai and 20 km of Sharjah, one would expect hundreds of deaths and in excess of 1000 injured, even for a M5.8 (Table VII). For an M6 earthquake the deaths and injured might number above 1000 and several thousand, respectively. The economic loss to building value in the four cities Dubai, Sharjah, Ajman and Al Quaywayn is calculated to reach \$3 billion in the four cities in case of an M5.8 earthquake (0.2–28% of the building value). In case of an M6 earthquake, a staggering \$5 billion (19–41% of the building value in the four cities) is expected to be lost.

The economic loss calculated here is an estimate of the cost to repair the damaged buildings, only. There are many other factors that contribute to the overall economic loss in earthquakes, such as damage to lifelines, production hiatus, emergency relief and medical costs. Thus, the total economic impact of any of the scenarios is far larger than the portion of it estimated here.

In the Abu Dhabi scenario we placed the epicenter at a distance of 30 km, hence there would be only several hundred casualties expected, even in an M6.2 event (Table VIII). We estimate that the 2% loss of building value represents approximately \$250 million.

6. Conclusions

1. The study is important for the UAE since until recent times earthquake hazard for this country was considered to be negligibly small. The earthquake with a relatively high magnitude of M = 5 which occurred in March 2002 demonstrated that this viewpoint has no grounds.

2. Because one cannot exclude the possibility that M6 ±0.5 earthquakes can happen in the UAE, we have to try and estimate what such an event could mean in terms of loss. The loss can be estimated only to an order of magnitude because the uncertainties in most parameters that are needed as input are large. Part of the value of this study is to help focus on the improvements needed in information to estimate the potential earthquake losses in the UAE more accurately, and hence to be able to prepare for such eventualities.

3. When we consider local earthquakes with magnitudes in the range of M6 ±0.5, we find that scenarios at the lower magnitude end are expected to have no serious effect, but at the upper end the catastrophes could be staggering, if the epicenter is near a major city. Unfortunately, a fault defines the western coastline. This means that all the major cities there, Abu Dhabi, Dubai, Sharjah, Ajman, and Al Quaywayn sit on top of this fault. If this fault is active, and we do not know, whether or not it is, then disasters with thousands dead and more than 10,000 injured could be in store. Another major fault, for which the activity level is also not known, runs through Dibba. This means that this city also could experience a major earthquake disaster. In the text, we give approximate numbers for deaths, injured, percent of buildings damaged, degree of damage, and loss in percent of the building value for a number of local earthquake scenarios that are plausible.

4. An earthquake in the Makran region of Iran could also cause some deaths, several hundred injured and loss of a few percent of the building value, if its magnitude reaches the maximum estimated for this region.

5. The estimates of losses presented in our tables could be severe underestimates if, as we fear, local soil conditions amplify strong ground motion, or lead to soil liquefaction. In earthquakes where these phenomena occurred, severe losses were sustained locally.

6. We faced a difficult problem resulting from the fact that there was no network of seismic stations in the UAE and data on historic earthquakes were poor. Micro zoning is not yet ready. Moreover, apparently, companies of various countries constructed houses in the cities of the UAE, using individual designs of buildings.

This made the assessment of houses vulnerability still more difficult. Therefore, risk estimates are tentative.

7. Studies that should be undertaken to reduce the uncertainties in these earthquake risk estimates are the following. (1) Establish a local seismograph network that is capable to accurately locate earthquakes down to magnitude M2. With this tool, active faults could be mapped and the probability for returns of events like the Masafi 2002 earthquake could be estimated. (2) The fragility of buildings in strong ground motion should be evaluated. (3) Microzonation of important cities according to soil conditions should be carried out, such that the amplification factors of strong ground motion could be estimated. (4) The numbers of inhabitants in all settlements should be more accurately determined.

8. It is clear that with the rapid urbanization in progress in the UAE and the real possibility of local earthquakes near cities, the seismic risk in the UAE is increasing rapidly, and should not be ignored.

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