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APPLICATION OF A STOCHASTIC METHOD FOR THE DEVELOPMENT OF EARTHQUAKE DAMAGE SCENARIOS: EILAT, ISRAEL TEST CASE

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This article summarizes the work done over the last 10 years regarding the development of a new approach for earthquake damage scenarios. The development process was tested in Eilat, Israel and involved microzoning of site effects across the city, monitoring of dynamic characteristics of buildings in Eilat, creating databases of the building inventory in the city and its population distribution and preparing a computerized GIS based application. The new approach is based on comparing the designed spectral acceleration level at the resonance frequency of a building with respect to the predicted level for the same building and for a given earthquake. The predicted spectral accelerations are computed by using the stochastic simulation technique of the ground motion spectrum, stochastic (Monte Carlo) simulations of an earthquake and the local site response function. The first test scenarios have demonstrated the applicability of the new approach that was also put to the test during the November 22, 1995 earthquake ($M_w = 7.1$) in the Gulf of Eilat/Aqaba. The predicted consequences of that earthquake, presented in scientific meetings few months before the earthquake occurred, agree well with later observations in Eilat, Israel. We also concluded that the "classical" approach, which is based on seismic intensity attenuation functions, yields exaggerated damage scenarios.

ПРИМЕНЕНИЕ СТОХАСТИЧЕСКОГО МЕТОДА ДЛЯ РАЗРАБОТКИ СЦЕНАРИЕВ РАЗРУШЕНИЙ ОТ ЗЕМЛЕТРЯСЕНИЙ НА ПРИМЕРЕ ЭЙЛАТА (ИЗРАИЛЬ)

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В статье обобщается многолетняя работа авторов по разработке нового подхода к сценариям разрушений от землетрясений. Подход демонстрируется на примере города Эйлат. Он включает микрорайонирование территории, анализ динамических характеристик для типичных сооружений города, создание базы данных по инвентаризации зданий города и распределению населения в нем на основе ГИС. Подход основан на сравнении расчетного уровня спектра ускорений на резонансной частоте здания с прогнозируемым уровнем для того же здания и данного землетрясения. Прогнозные значения спектра ускорений вычислялись с помощью статистического метода моделирования спектра движения почвы, стохастического (по Монте Карло) моделирования землетрясения и локальной функции отклика. Один из расчетных сценариев прошел успешную проверку землетрясением с $M_w = 7.1$ 22 ноября 1995 года в Эйлатском (Акабском) заливе. Прогнозируемые последствия сходного землетрясения в Эйлате были доложены на научных конференциях за несколько месяцев до указанного события 1995 года и оказались в хорошем согласии с реальными наблюдениями. В работе делается заключение для Эйлата, что "классический" подход, основанный на законах затухания балльности, завышает ожидаемые разрушения.

Introduction

In order to mitigate earthquake risk and initiate preparedness plans, we must be able to estimate the possible consequences of strong earthquakes, i.e., implement our accumulated experience of past earthquakes to present a scenario of an eventual earthquake. The call "be prepared!" must be supported by the ability to provide a realistic picture of the consequences of a destructive earthquake. In the early 90's, a small group of scientists formed the IASPEI Working Group for Earthquake Risk and Loss Assessments. In the framework of the Working Group's, the Gulf of Eilat/Aqaba was selected as a test area focusing on developing methods of preparing earthquake scenarios for the town of Eilat, Israel. Eilat is a relatively small city but includes a variety of structures, facilities of national importance, varying geological conditions over a relatively small area and has all the main elements of a major city. Eilat is located on the seismically active Dead Sea Transform that has generated +7 magnitude earthquakes in the past. Recent paleoseismic studies near Eilat show displacements/ruptures caused by high magnitude seismic activity with relatively long average return periods (see [1]).

In recent years, there have been an increasing number of attempts to predict the consequences of destructive earthquakes. Among the many we mention here Molchan et al. [2]; Keilis-Borok et al. [3]; ATC-13 [4]; Erdik and Tucker [5]; Fu [6]; Chen Yong [7]; Fah [8]; Shakhmanjyan [9]. In the works cited above, earthquake damage scenarios are evaluated directly from predicted seismic intensities. Evidently seismic intensity is still commonly used to quantify earthquake risk. Implementation of seismic intensities in predicting the effects of an earthquake depends heavily on good macro-seismic evidence relevant to the geological, geotechnical, engineering and demographic conditions that characterize the study area. As long as these parameters are more or less stationary, the predicted scenarios may be considered reliable. This, however, is not the case for large parts of the world where the demography and the engineering properties of houses and buildings are constantly changing. Apparently, the most rapid changes are associated with the quality of structures and their vulnerability to seismic ground shaking and such is the case for Israel. The Holy Land has a long, documented history of destructive earthquakes. However, the demographic conditions, engineering characteristics of the buildings and structures and even the geographical (and, thus, geological) location of the settlements and villages are very different from those that existed in the past. The detailed investigation of the 1927 Jericho earthquake (Avni [10]) is probably the most accurate and complete macroseismic study of the region. And yet, it is of limited use because of the great changes the region has undergone in the last 50 years. In this respect, the town of Eilat may be considered a good representative of a wide class of cities that are vulnerable to earthquakes but for which there are no intensity data associated with the city (or its vicinity) that can be used to prepare a realistic scenario.

During 1991–1995 we developed the methodology (described in the following) and the graphical tools to prepare and present an earthquake scenario for Eilat. The methodology developed is based on the concept that vibratory motions, especially those leading to resonance motions of buildings, are the main cause of extensive damage and destruction. Consequently, the method is based on comparison of the design acceleration response spectrum of a building with a predicted site-specific acceleration response spectrum from a prescribed earthquake. This approach advocates reliance on analytical evaluations that are, in turn, based on basic seismological and engineering parameters rather than on empirical intensity relationships. On November 22, 1995 a strong earthquake ($M_w = 7.1$) occurred in the Gulf of Eilat (Aqaba). The epicenter of that earthquake was located about 100 km south of Eilat. The ruptured fault of about 40 km (Shamir [11]) is about 60 km. distant from the center of the city. This earthquake provided a unique opportunity to compare the observed intensities across the city with the predicted effects. This comparison revealed a good fit between observations and predictions. It should be emphasized that the predictions were made two months before the occurrence of the Gulf of Aqaba earthquake and were presented in September 1995 in China (Shapira et al.[12]). This was also a unique opportunity to compare the evaluations made by the new method with those obtained using the common procedure of preparing earthquake scenarios based on correlation functions between seismic intensities, magnitude and distances. The latter was found to provide severely exaggerated effects of that earthquake.

1. Methodology

The almost classical approach for developing earthquake scenarios is based on direct prediction of the seismic intensity from an empirical function that correlates between the magnitude of the event, the hypocentral distance and the predicted seismic intensities (see, for example, Feldman and Shapira [13]). The intensity is then "corrected" for the local geological conditions by adding (in soft soil conditions) or subtracting (in hard rock conditions) a fraction of an intensity unit and up to 2 units (see Wachs [14]). The latter process is somewhat odd, considering that the units of any intensity scale are by definition discrete integers. During the years, damage matrices have been developed. These matrices provide an estimate of the percentage of buildings that will suffer a certain degree of damage for a given seismic intensity. Different matrices should correspond to different types of buildings. An example copied from the ATC-13 [4] is shown in Table 1.

TABLE 1. Probabilities of Damage

Degree of Damage	Central Damage Factor, %	Probability of Damage, % VI	VII	VIII	IX	X	XI	XII
None	0.	95.0	49.0	30.0	14.0	3.0	1.0	0.4
Slight	0.5	3.0	38.0	40.0	30.0	10.0	3.0	0.6
Light	5.	1.5	8.0	16.0	24.0	30.0	10.0	1.0
Moderate	20.	0.4	2.0	8.0	16.0	26.0	30.0	3.0
Heavy	45.	0.1	1.5	3.0	10.0	18.0	30.0	18.0
Major	80.	0.0	1.0	2.0	4.0	10.0	18.0	39.0
Destroyed	100.	0.0	0.5	1.0	2.0	3.0	8.0	38.0

Copied from [4]

Similarly, experience also tells us of the expected rate of casualties at each eventuality of a damage grade (Table 2).

TABLE 2. Expected Rate of Casualties

Degree of Damage	Central Damage Factor, %	Probability: Fraction of Injured, Minor	Probability: Fraction of Injured, Serious	Probability: Fraction of Fatalities
Slight	0.5	3/100,000	1/250,000	0.000001
Light	5.0	3/10,000	1/25,000	0.000010
Moderate	20.0	3/1,000	1/2,500	0.000100
Heavy	45.0	3/100	1/250	0.001000
Major	80.0	3/10	1/25	0.010000
Destroyed	100.0	2/5	2/5	0.200000

Copied from [4]

Any scenario that is prepared using this classical approach must be based on up-to-date, relevant and reliable information. Such might exist in areas where, unfortunately, suffer frequently from disastrous earthquakes.

This study stems from the fact that such "good data" do not exist for Israel. Despite the long documented history of destructive earthquakes in the Holy Land and the wealth of documents describing the effects of earthquakes throughout the region, the use of seismic intensities is rather limited. The types of buildings currently characterizing the building stock in Israel are very different from those that existed in the area throughout the previous centuries. Furthermore, the distribution of the population and its density in now way matches the situation only 50 years ago. Lacking any empirical information about seismic intensities that are relevant to the current engineering and demographic conditions, it was necessary to develop a new methodology in which the seismic intensities could be predicted from the physical parameters that characterize the interaction of ground shaking and buildings.

A series of studies, including those of Shapira and van Eck [15], have demonstrated that the stochastic method of Boore [16], Boore and Atkinson [17], Boore and Joyner [18] and others is very useful for predicting the acceleration response spectrum. When convolved with the site response function of a given site, we can obtain a reliable estimation of the site-specific acceleration spectrum. In the current version, we used the Joyner [19] computer code to compute the site response function of a site, given its subsurface model. Shapira and van Eck [15] have used Monte Carlo statistics to incorporate the uncertainties associated with the parameters needed in the simulations. In a wider application (i.e., seismic hazard assessment) we term this approach as the SvE and use it to estimate the site-specific, uniform hazard acceleration response spectrum. In the current application for preparing an earthquake scenario we use the SvE approach to compute the expected acceleration response spectrum (i.e., the maximum acceleration levels for different frequencies representing a set of single degree of freedom oscillators with a given damping ration) from an earthquake of a known magnitude and known distance to a given site.

Modern buildings in Israel are built in accordance with Israel Standard 413 (IS-413). This building code, as many other modern codes around the world, defines the seismic design parameter as the spectral acceleration level at frequency f_0 of the design acceleration response function. This function is usually obtained by renormalizing a standard response spectrum, i.e., the standard response spectrum (damping ratio of 5%) is multiplied by the design peak ground acceleration level (usually computed for an exceedence probability of 10% in an exposure time of 50 years). The local geology is introduced by multiplying the whole function by a safety coefficient (a factor of up to 1.2). Note that the re-normalized response spectrum is the design acceleration response spectrum.

The frequency f_0 (or its reciprocal value T_0) is the fundamental resonance frequency of the structure, which is primarily dependent upon the height of the building. Let us denote Z_d as the design acceleration level of the building at frequency f_0. If the building was designed and constructed according to the IS-413, than Z_d is read from the renormalized response spectrum.

Let us denote Z_s as the acceleration response level at f_0, computed by the SvE process for the particular site conditions. At this point we *suggest* that the earthquake vulnerability of a building is directly related to the ratio Z_d/Z_s (hereafter, termed the vulnerability parameter, ν). The parameter ν actually provides a quantitative measure of two vulnerability components: (a) the proximity to resonance of the structure's motion and (b) the discrepancy between the design level of motion and the actual motion that the structure experiences.

Fig. 1 presents the hypnotized relationship between the damage rate as a function of the vulnerability factor $\nu = Z_d/Z_s$. It has to be emphasized that this figure is primarily based on subjective interpretations of damage reports in the ATC-13 report [4] and in other sparse descriptions of damage to engineered structures during recent earthquakes. Unfortunately, we do not have an analytical presentation of that relationship. At present, we use Fig. 1 and we shall modify it when empirical data becomes available.

2. Why Eilat?

Eilat is an ancient city dating back to the times of King Solomon and the Queen of Sheba. In the ancient world it was, as today, the main gate to Africa and Southeast Asia. Historical documents (Amiran et al. [20]) describe severe destruction in Aila (the Arabic name for Eilat) in 1068 but the evidence is very fuzzy. Seismic monitoring in the Middle East started in 1891 (HLW station in Egypt) but it was not before March 1969, with the $M_s = 6.6$ Sharm el Shekh earthquake, that the area of the Gulf of Eilat/Aqaba was considered significantly active. Eilat is located in one of the segments of the Dead Sea Transform fault system, (e.g Garfunkel [21]; Ben Avraham [22]; Ben Avraham and Tibor [23]; Shamir and Shapira [24]). Some of the active faults run across the city. After a long quiescence, a series of earthquake swarms hit the Gulf of Eilat, escalating to the $M_w = 7.1$ earthquake on November

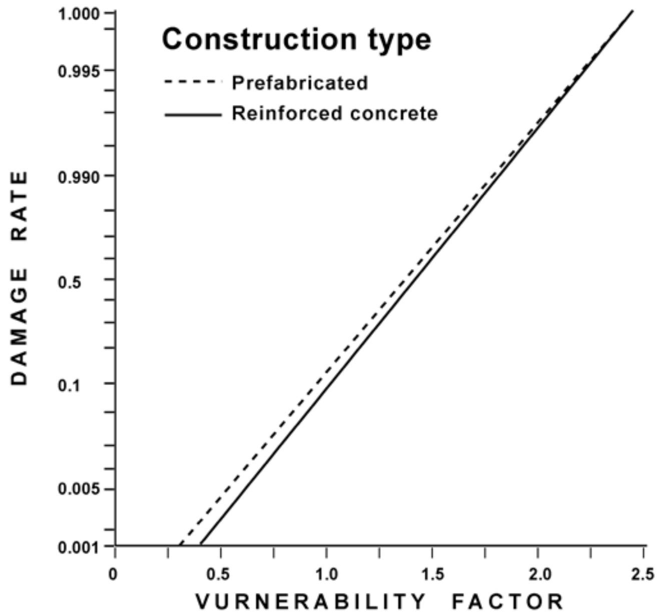

Fig. 1. Suggested Vulnerability Functions

22, 1995 (see, for example, El-Isa [25]; Al-Amri [26]; Al-Amri [27]; Shapira [28]; Shamir [11]).

Eilat is a small town of about 30,000 inhabitants (in 1991). It is a well-known vacation resort that attracts daily some 5,000-10,000 local and foreign tourists. The town is small enough to enable us to carry out a detailed survey of all the structures and buildings in the city and yet it is big enough to host an airport, a seaport, a small industrial zone and a relatively large vacation resort. Owing to the small dimensions of the town, we could afford to collect detailed information about on the 3,000 buildings in the town and their inhabitants and on site effects across the city. Consequently, Eilat was chosen for a pilot project for developing a method to prepare an earthquake scenario. All the information was stored on a specially designed GIS for PC. This software has served for many years providing the authorities in Eilat with damaging earthquake scenarios that were used to intensify preparedness plans for use in the event of a serious earthquake.

3. Seismic microzoning of Eilat

Seismic wave amplification due to sedimentary deposits is one of the most important parameters influencing seismic hazard and earthquake risk. Site effects associated with ground motion amplification at the resonance frequency of a building may become devastating. Various empirical techniques using earthquake data for site response estimation have recently been summarized and discussed (Field et al. [29]; Field and Jacob [30]). The site response functions are best determined from recorded ground motion during an actual strong event by means of comparison with recordings at a nearby reference site located on rock. However, in most cases, mainly in regions where the seismic activity is relatively low as in Israel, this type of analysis is usually impractical. Many investigators evaluated site response functions from moderate to weak motions of earthquakes (Tucker and King [31]; King and Tucker [32]; McGarr et al. [33]; Field and Jacob [34]; Field [35]; Liu et al. [36]; Jongmans and Campillo [37]; Carver and Hartzell [38]; Hartzell et al. [39]; Steidl et al. [40]; Toshinawa et al. [41]; Zaslavsky and Shapira [42]). Evaluation of sediment-to-bedrock spectral ratio (classical technique) for estimating site response depends on the availability of an adequate reference site.

Lermo and Gaves-Garcia [43] drew significant results from a non-reference technique that involves a receiver function, i.e., using the horizontal-to-vertical component spectral ratios of shear-wave. Many studies report that the frequency dependence of site response can thus be obtained from only one station (Lermo and Chaves-Garsia [44]; Theodulidis et al. [45]; Seekins et al. [46]; Malagnini et al. [47]; Zaslavsky et al. [48]; Zaslavsky, Shapira and Leonov [49]). The implementation of this approach, however, still requires the rather frequent occurrence of earthquakes.

Nakamura [50] hypothesized that site response could be estimated by dividing horizontal component noise spectra by vertical component noise spectra. Theoretical studies (Field and Jacob [34]; Lachet and Bard [51]; Coutel and Mora [52]; Konno and Ohmachi [53]) and results obtained by implementing the Nakamura technique (Ohmachi et al. [54]; Lermo and Chaves-Garcia [44]; Field and Jacob [30]; Zaslavsky et al. [55]; Seekins et al. [46]; Gitterman et al. [56]; Teves-Costa et al. [57]; Konno and Ohmachi [53]; Mucciarelli [58]; Zaslavsky, Shapira and Arzi [59]) support such use of microtremor measurements to estimate the site response for surface deposits.

Ground motions were recorded using the multi-channel, PC-based, digital seismic data acquisition system (see Shapira and Avirav [60]) designed for site response field investigations. One vertical and two horizontal seismometers (oriented north-south and east-west) were installed at each station. The horizontal-to-vertical spectral ratio $[A_{H/V}(f)]$ was obtained by dividing the individual spectra of the horizontal components of the site $[S_{NS}(f)$ and $S_{EW}(f)]$ by the spectrum of the vertical component $[S_V(f)]$ of the site. The arithmetical average of each horizontal-to-vertical component ratio was computed. We observed that averaging the ratio components arithmetically or geometrically does not significantly alter the results. If average ratios of the NS and EW components are similar, the average of the two horizontal-to-vertical component ratios will be the site amplification function:

$$A = \frac{\sum_1^n S_{NS}(f)_i + \sum_1^n S_{EW}(f)_i}{2\sum_1^n S_V(f)_i} \tag{1}$$

Most of the city of the Eilat is situated on alluvial fans composed of poorly consolidated conglomerates, marine and lacustrine Holocene sediments. Fig. 2 shows the thickness of the sediments above the granite basement. The basement depth varies from 0 to 300 meters to the west of the main Dead Sea transform fault and from 300 to 3000–5000 meters east of the main fault. The contrast in stiffness between the granites and the overlying sediments will cause the effect of frequency selective amplification of the seismic ground motions. Fig. 3 presents the average horizontal-to-vertical spectral ratios obtained from microtremors at stations 1, 2, 3, 4 and 6 (The station locations are shown in Fig. 7).

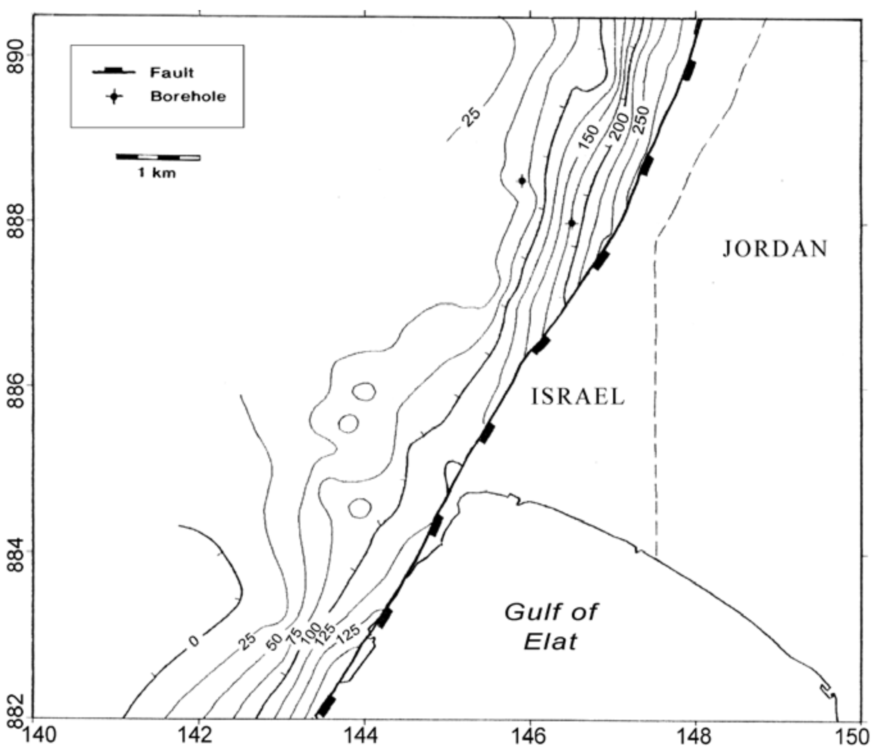

Fig. 2. Thickness of the sediments above the Granite basement in Eilat

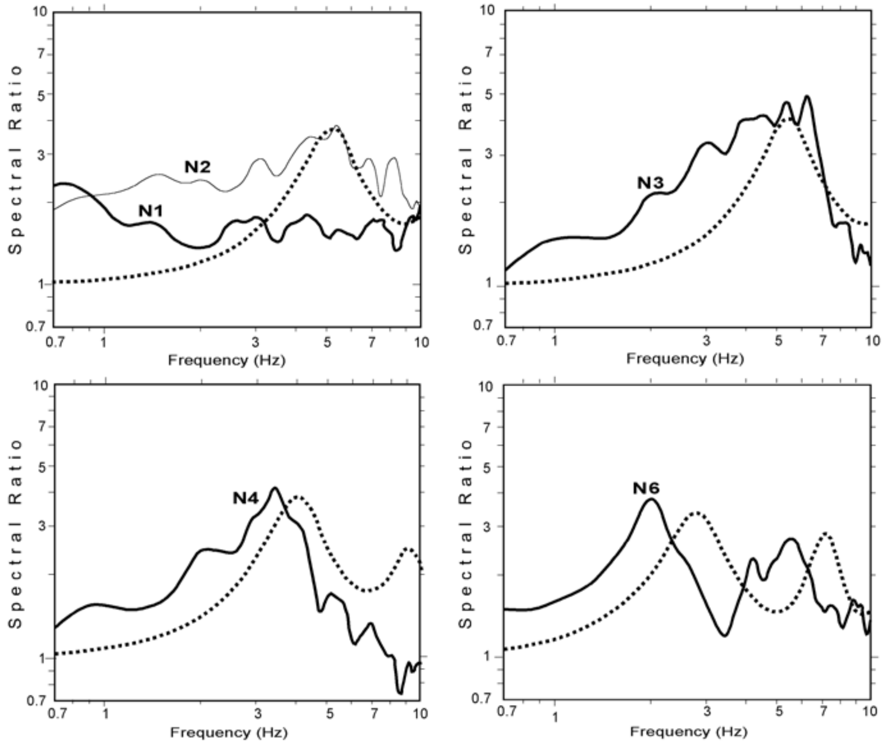

Fig. 3. Average horizontal-to-vertical spectral ratios obtained from microtremors at stations 1, 2, 3, 4 and 6

Station 1 is installed on the granite rock and its response, therefore, is almost flat over the entire frequency range and there is no indication of site effect. Stations 2, 3, 4, 5 and 6 are on sediments and we can see that the predominant frequency varies from 6 to 2 Hz over only 500 m. The spectral amplification factor remains constant and is of the order of factor 4. Subsurface modeling and the Joyner [19] computer program are used to calculate the theoretical site response function (see the dotted line in Fig. 3). The numerical models of the subsurface are derived from P- and S-wave refraction survey (Shtivelman [61]). The refraction line was 500 m in length and was stretched along stations 1–6 (Fig. 4). The first layer velocity relates to sand, the second layer to conglomerate and the third layer is characteristic of the crystalline basement (granite).

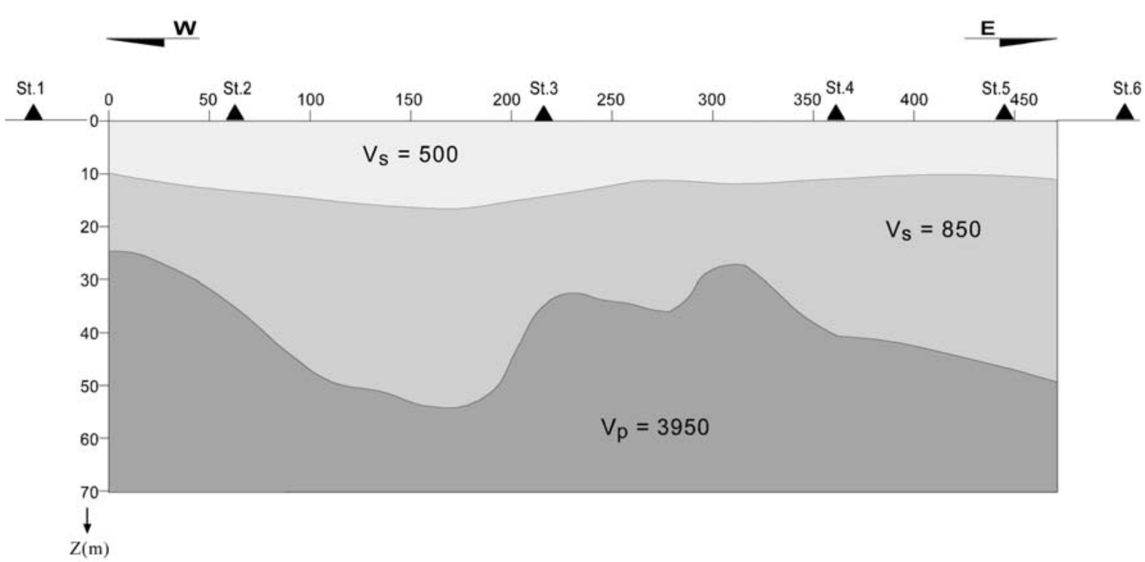

Fig. 4. Depth section along refraction line stations 1 to 6

A special site response study took place in the Eilat football stadium (station 26). Significant differences of predicted site effects exist between the measurement points within very short distances (several tens of meters). Two of the analyzed points are located on the rock and the ratio functions are relatively flat over the entire frequency range while at two other points we see an amplification of approximately 6 at about 6 Hz.

Fig. 5 shows the average horizontal-to-vertical spectral ratios obtained from microtremors at stations 14, 15, 16 and 18, located in the Eilat resort area. A first order description of site response in this area has a prominent peak at 1.0 to 1.5 Hz with amplification factors of up to 3.0-3.5. Similarly, we have obtained the empirical response functions for the other sites/stations across the city.

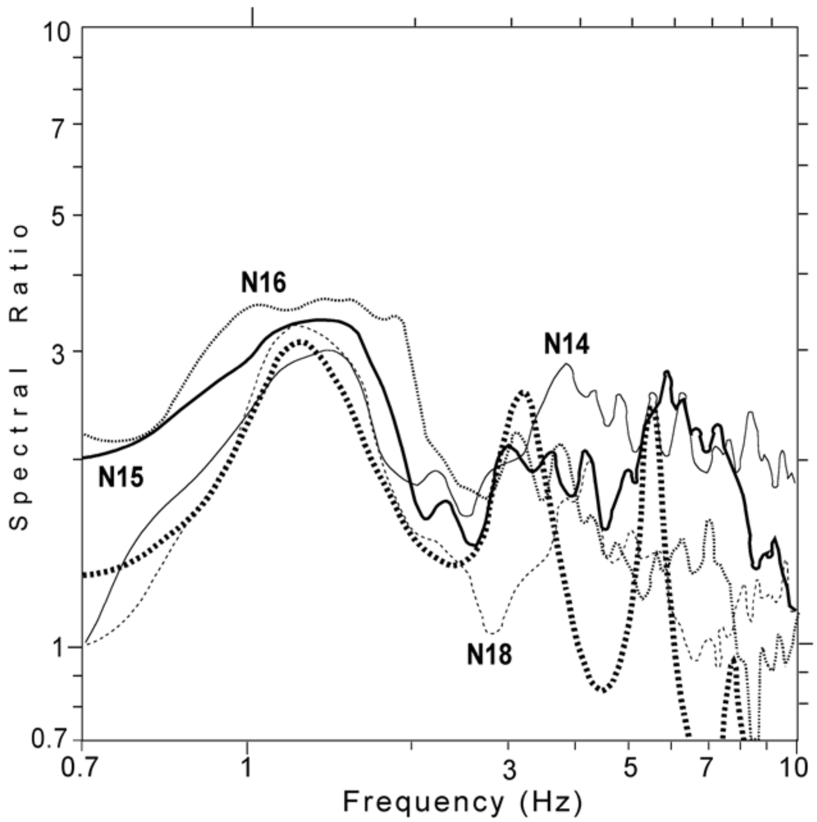

Fig. 5. Average horizontal-to-vertical spectral ratios obtained from microtremors at stations 14, 15, 16 and 18

The varying surface geology across the city implies strong variations in the expected site effects within distances of only several tens of meters. Hence, it is practically impossible to predict the site effect characteristics at every arbitrary point in the city. Based on surface geology information (Y. Bartov, personal communication), velocity depth maps (Kravtsov et al. [62]; Shtivelman [61]) some borehole data and the site response measurements at 26 stations, we compiled the soil-column models shown in Fig. 6. These generalized soil-columns characterize the six zones of Eilat. The distribution of the zones is summarized in Table 4 and shown in Fig. 7. Table 3 presents a good fit between the resonance parameters at the 26 stations as obtained by seismological measurements and the corresponding analytical values that are computed by using the parameters of the suggested zonation map

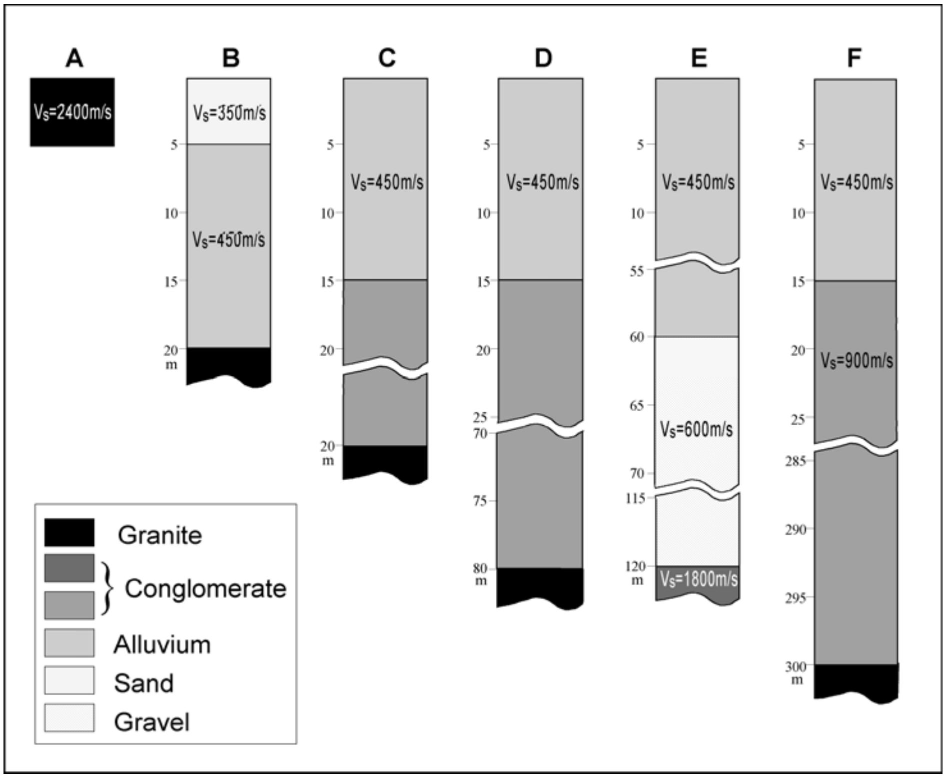

Fig. 6. Typical soil-column models for Eilat

TABLE 3. Empirically and Analytically Estimated Site Response Values in the Study Region

Site Number	Observed		Calculated	
	Resonance Frequency	Amplification	Resonance Frequency	Amplification
1	–	–	–	–
2	5.2	3.8	5.2	3.8
3	6.0	4.2	5.5	4.0
4	3.5	4.2	4.0	3.8
5	2.6	4.9	3.4	3.5
6	2.1	3.7	2.8	3.4
7	4.3	4.3	3.7	3.6
8	1.8	3.0	2.2	3.3
9	2.5	2.5	2.8	3.4
10	1.6	2.0	1.8	2.3
11	*	*	1.5	2.5
12	1.3	2.5	1.2	2.5
13	1.5	1.5	1.2	2.0
14	1.4	3.0	1.4	3.2
15	1.4	3.4	1.4	3.2
16	1.4	3.7	1.4	3.2
17	1.2	3.8	1.4	3.2
18	1.2	3.3	1.4	3.2
19	0.7	3.0	0.8	3.0
20	3.0	3.5	2.8	3.4
21	0.8	3.5	0.8	3.0
22	0.8	4.8	0.8	3.0
23	*	*	0.8	3.0
24	1.2	3.2	1.2	3.2
25	2.5	4.0	2.8	3.6
26	5.4	6.5	5.7	5.7

* Predominant frequency is not detectable by the applied procedures

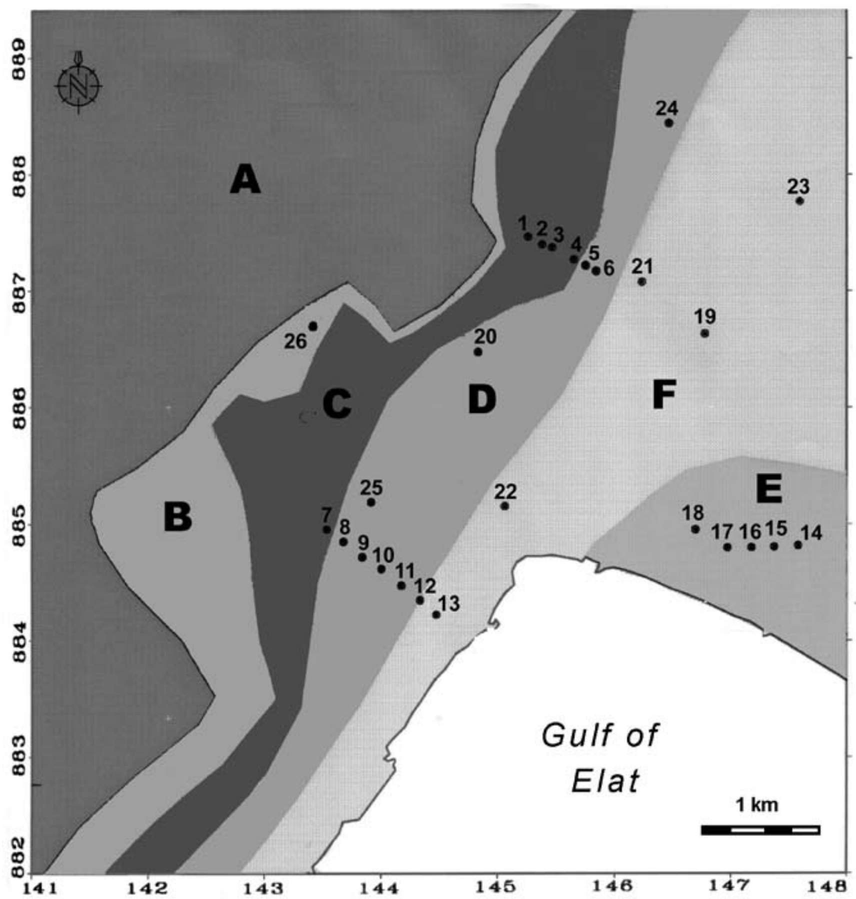

Fig. 7. Seismic microzoning map of Eilat (Also shown are locations of 26 stations where site-response measurements were made)

TABLE 4. Generalized Amplification Effects in the Six Zones of Eilat

Zone	Parameters of Site Effect		
	Resonance Frequency (Hz)	Amplification Factor	dI
A	–	1	−1.0
B	5–8	6	0.2
C	3–5	4	0.5
D	1.5–3	3.5	0.5
E	0.8–1.5	3.0	1.0
F	< 0.8	3.5	1.0

4. Dynamic characteristics of low rise buildings in Eilat

The damage caused to a structure can be especially strong if the ground shaking contains frequencies that are close or at the natural frequency of structure, f_0.

The database of buildings in Eilat included information on the height of the building. In many buildings codes (see, for example, Luft [63]) the natural frequency of a structure is estimated to the first order by the formula:

$$\mathbf{f} = 10/\mathbf{N}, \tag{2}$$

where **f** is the natural frequency in Hz and **N** is number of stories for the building.

In our first exercises we have adhered to this formula for the purpose of estimating f_0. As a second approximation, we conducted a series of measurements on low-rise buildings in Eilat. The measurement equipment consists of the temporary installation of two three-component seismograph stations on the roof and at the foundation. The fundamental frequencies of the longitudinal and transverse vibrations of the buildings are determined through spectral ratio computations (roof to foundation) of seismic signals: earthquake, ambient noise and forced vibrations of unknown origin. Examples of empirical functions are presented in Fig. 8. The results are summarized in Table 5 (see also Zaslavsky and Shapira [64]; Zaslavsky and Shapira [65]; Zaslavsky et al. [66]).

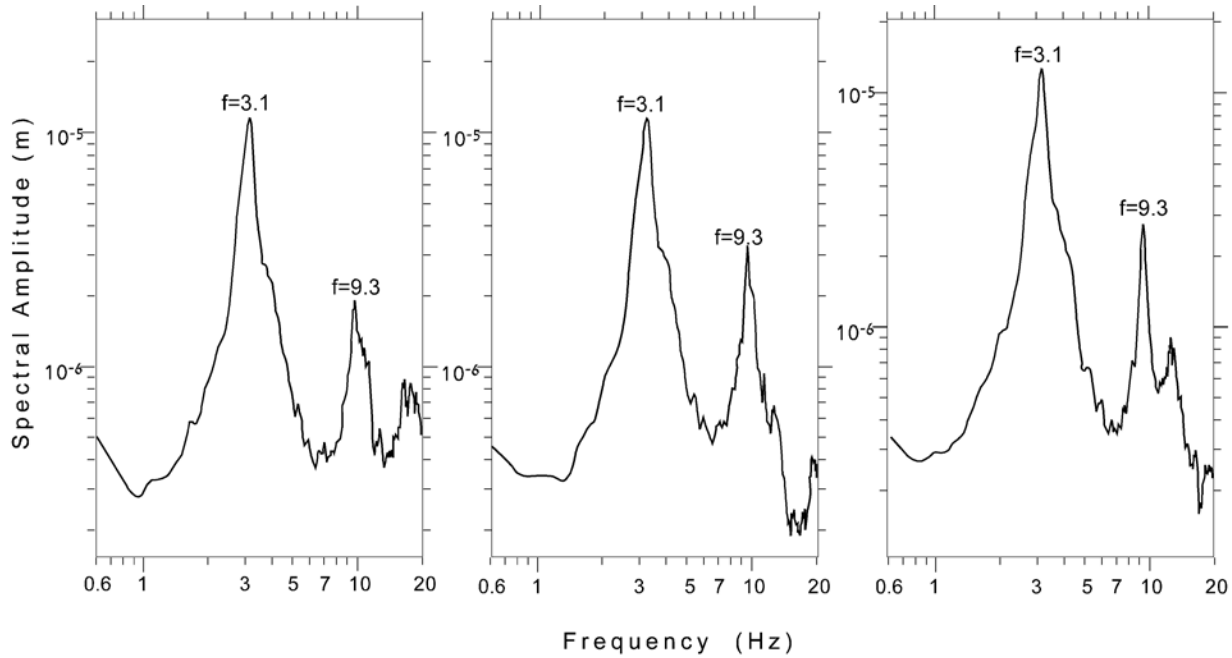

Fig. 8. Average amplitude spectra (EW direction) of ambient noise at stations located on the roof of the High School building

The empirically evaluated natural frequencies differ significantly from those suggested by (2). The measured fundamental frequencies are about 1.8 times higher than those previously predicted.

TABLE 5. Dynamic Characteristics of Selected Buildings

Building	No. of Stories	Fundamental Natural Frequency (Hz)			Damping Ratio (%)	
		NS	EW	Torsion	NS	EW
Mekorot	2	8.5	9.5	–	6.0	7.0
Tze'elim School	2	8.8	8.3	–	3.0	4.0
Yigal Alon School						
Section 1	2	8.6	9.8	–	6.0	6.0
Section 2	3	5.3	5.3	–	5.0	5.0
High School	3	4.3	3.1	7.0	5.0	4.0
Etzion Gaver Sch.	3	4.8	3.9	–	4.0	4.0
Ofir School:						
Section 1	3	8.3	5.8	11.8	–	–
Section 2	3	6.7	4.7		–	–

Two different approaches were tested for earthquake loss estimation. We estimated direct losses only caused by building damage.

5. Earthquake damage scenario for Eilat

An in-house GIS program was written to facilitate data archiving and editing. This program was also used to compute the acceleration values Z_d and Z_m for each of the buildings in Eilat. In order to facilitate these computations, the user must interactively define the magnitude of the earthquake and the location of the fault rupture. Figs. 9 and 10 show two examples of the acceleration response spectra for the six zones in Eilat and of the design acceleration response spectrum for Eilat at the current Israel Standard 413. In the first example (Fig. 9) we assume an earthquake of magnitude 7 that occurred 80 km south of Eilat in the Gulf. In the other example (Fig. 10) we defined an earthquake of magnitude 6 that occurred 50 km north of the city.

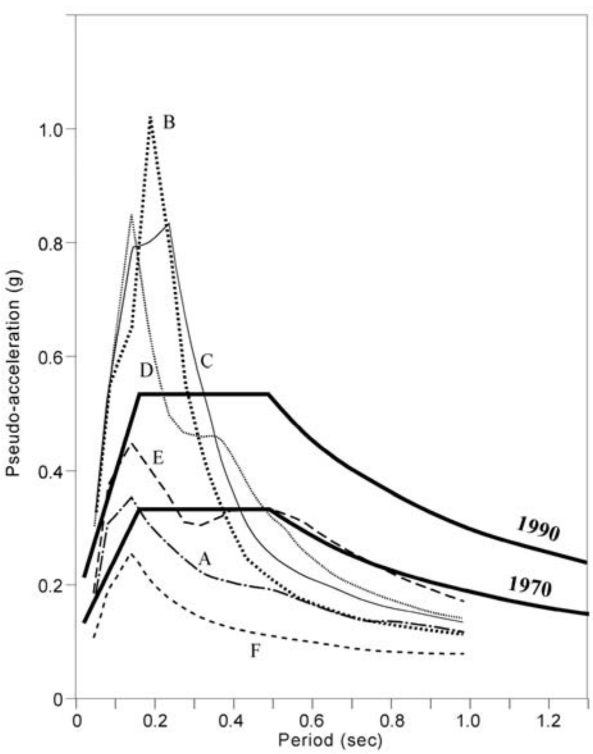

Fig. 9. Acceleration response spectra for the six zones in Eilat calculated for an earthquake of magnitude 7 that occurred 80 km south of Eilat in the Gulf. Also shown are design acceleration response spectra for Eilat: current Israel Standard 413 (1990) and previous Israel Standard (1970)

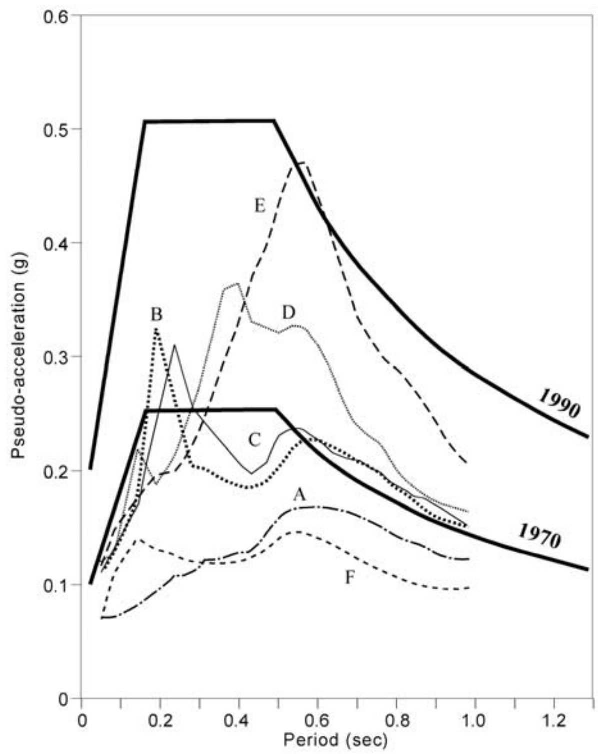

Fig. 10. Acceleration response spectra for the six zones in Eilat calculated for an earthquake of magnitude 6 that occurred 50 km north of Eilat. Also shown are design acceleration response spectra for Eilat: current Israel Standard 413 (1990) and previous Israel Standard (1970)

For simplicity's sake, we have treated all buildings in Eilat to be classified as re-enforced concrete buildings. The majority of the buildings in Eilat are of this type. For this type of building we suggest the vulnerability curve shown in Fig. 1. The fundamental frequency of each building is estimated with respect to its height (see previous paragraph). Under these assumptions, we proceed as follows:

(1) The natural frequency f_0 of the building is estimated from its height.

(2) Based on f_0 we obtain Z_d.

(3) For a predefined magnitude and epicenter location and for a known site we compute the expected acceleration response spectrum (damping ratio of 5%) and obtain the value of Z_m that corresponds to f_0.

(4) The vulnerability coefficient (ν) and the degree of damage (Fig. 1) are determined.

(5) Following step (4), each building in Eilat is assigned a damage rate and, hence, a damage grade that corresponds to the damage grade definition of the ATC-13 report [4] (see Tables 1 and 2).

(6) Given the date and time of the event, casualties are estimated at each building, depending on its occupancy with respect to the season (applicable mainly for hotels) and the time of day.

Table 6 presents results of damage scenarios that corresponds to cases presented in Figs. 9 and 10, respectively.

TABLE 6. Damage Scenarios for Two Events Near Eilat

Damage State	Number of Buildings			
	$M = 7.1$, $R = 80$ km		$M = 6.5$, $R = 50$ km	
	Classical approach	SvE approach	Classical approach	SvE approach
Destroyed	21	0	4	0
Major damage	43	0	9	0
Heavy damage	68	0	15	0
Moderate damage	169	64	26	0
Light damage	336	1233	94	0
Slight damage	836	474	383	3
No damage	648	354	1396	1928

Discussion

This paper describes the first attempt made in Israel to quantify the effects of a destructive earthquake. The innovative works of Keilis-Borok [67], Keilis-Borok [68] have served as a trigger for this study. Following the presentation of Keilis-Borok at the IUGG meeting in Hamburg, Germany, we were quite puzzled by the question of whether seismic intensity is a suitable tool to use to estimate an earthquake scenario. It seemed to us that most of the major cities of the world that are vulnerable to earthquake hazards are lacking applicable intensity information and we, thus, used Eilat as a pilot project for an alternative methodology.

By comparison, we used the scenario events of magnitudes 7.1 and 6.5 to estimate the consequences of those earthquakes through directly evaluating the intensities. Here we adopted the equation of Feldman [13]:

$$I = 0.7 + 1.6 \times M_L - 2.5 \times \lg(\Delta) - 0.003 \times \Delta, \qquad \text{for} \quad M_L \geq 6.0. \tag{3}$$

Here, I is the expected, on the average (i.e., NOT maximum intensity), at a distance of Δ km from the epicenter. Equation 3 is based on intensity information from earthquakes that have occurred in Israel and adjacent countries. Based on the type of soils of the surface geology, we have added dI values (i.e., "intensity corrections") as specified in Table 4 above. Then, introducing the damage matrices given in Table 1, we obtained the estimated damages and casualties. Applying this process to different earthquake scenarios and comparing the predicted values we observed that the so-called "classical" approach yields far more severe damage (and consequently, casualty) scenarios, as compared with the SvE approach. This trend has repeated itself with many different examples of earthquakes with magnitudes varying between 5.5 to 7.5 and distances of 30 to 150 km.

An earthquake of magnitude $M_w = 7.1$ occurred in the Gulf of Eilat/Aqaba on November 22, 1995. This is the ONLY event that we may use as reference for our scenario predictions. Fig. 11 shows the isoseismal map that has been constructed for Eilat based on a detailed survey of the city conducted by teams of engineers (see also Al-Tarazi [69]). This isoseismal map is drawn on the zonation map of Eilat and corresponds very well with the predictions made by implementing the SvE approach. The predictions made through the "classical" approach evidently lead to considerable exaggeration.

The Gulf of Aqaba earthquake cannot be used as proof that all parameters used in the SvE approach are correct. The very good fit could still be mere coincidence. Much better engineering judgment is required in order to define the vulnerability function and typify the buildings in Eilat and elsewhere in Israel. The intensities observed in Eilat, however, support our criticism of the applicability of intensity attenuation functions that are derived from historical macroseismic evidence.

The graphic systems and data bases prepared for Eilat enabled us to prepare a number of realistic earthquake damage scenarios that were used by the local authorities for training and improved preparation for a strong earthquake that will eventually occur.

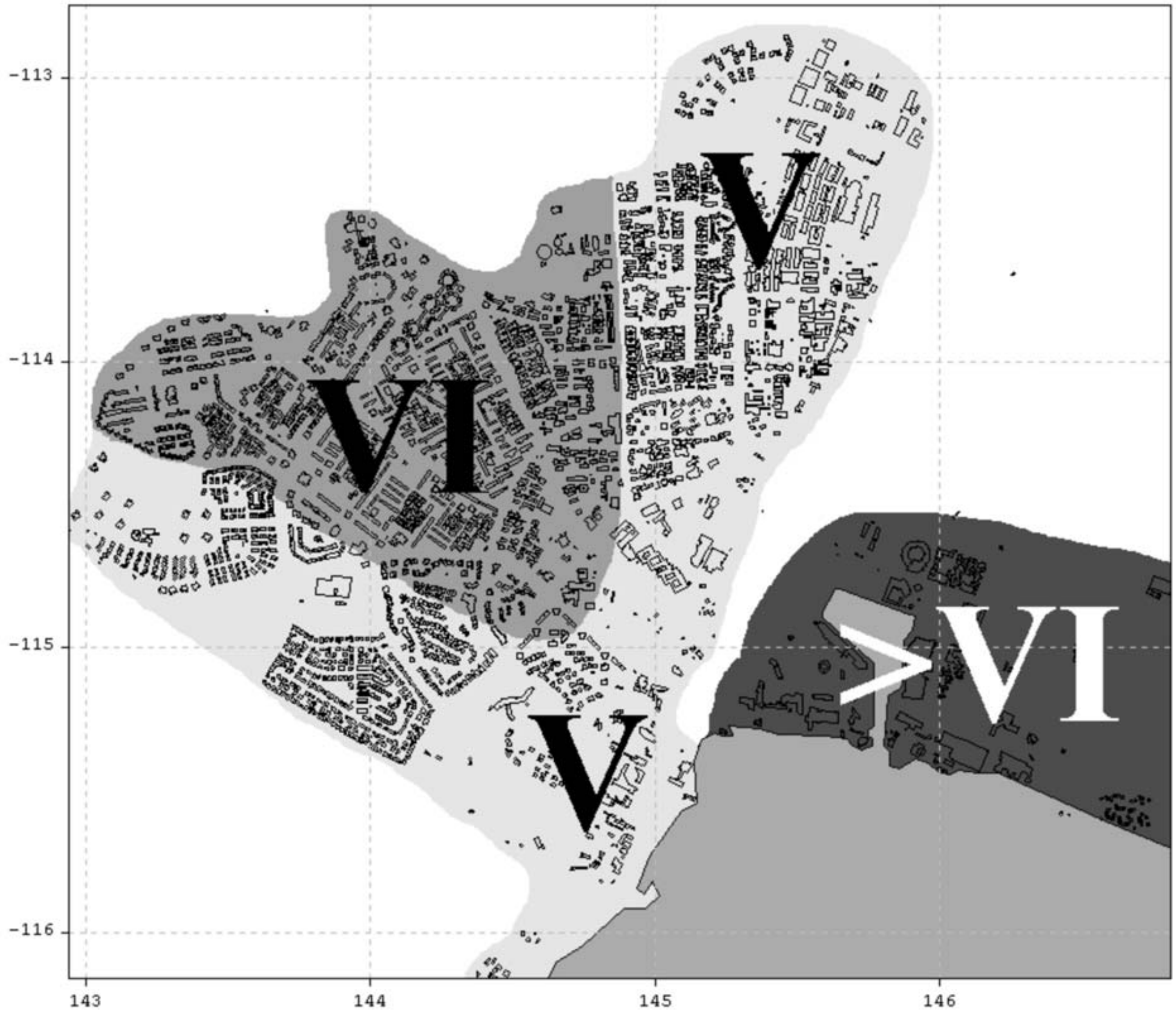

Fig. 11. The observed isoseismal map of Eilat from the Gulf of Aqaba earthquake

We thank the municipality of Eilat for supporting this project by helping us gather information before and after the Gulf of Aqaba earthquake and facilitating the seismological survey of the schools. Without the direct involvement of the municipality of Eilat and the mayor, Mr. G. Kadosh, this project would not have been possible. The dedication and enthusiasm of our colleagues at the Geophysical Institute of Israel, especially David Kadosh, David Levi, Uri Peled and Yossi Swartz were the main force behind the success of this project. Our sincere thanks to Dr. Y. Bartov for his encouragement and sound geological advice. This project was financed by the Earth Science Research Administration of the Ministry of National Infrastructures.

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