Structural Eng./Earthquake Eng., JSCE, Vol. 19, No. 2, 99s—111s, 2002 July
(J. Struct. Mech. Earthquake Eng., JSCE, No. 710/ I —60)

SEISMIC RISK IN GREECE: WHAT RECENT EARTHQUAKES HAVE TAUGHT US

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The following factors are identified to have a critical effect on seismic risk in Greece. First, exposure to seismic hazard is strongly non-uniform, with over half of the country's 10 million population – and accordingly most of the industry and infrastructure – concentrated in only two major urban conglomerates. In addition, many of the potentially damaging earthquakes occur in sparsely populated areas or have their foci under the sea. Last, the enforcement and upgrading of seismic codes since 1959, in combination with a generally good quality of construction materials and workmanship, contribute to a relatively reduced vulnerability of structures.

Key words: *Greece, seismic risk, seismic hazard, seismic codes*

1. INTRODUCTION

Seismic risk (SR) is determined, apart from seismic hazard (SH), by another two factors: exposure to hazard (E) (e.g. population, number of dwellings, etc.), and vulnerability of structures (V). Mathematically this relationship is expressed as

$$SR = SH*E*V,$$

i.e. for a given level of seismic hazard, the higher the exposure and vulnerability of a structure, the higher the seismic risk to which it is subjected. The seismicity of the Eastern Mediterranean is by far the highest in Europe and among the highest worldwide (e.g. Papazachos and Papazachou[1)]). This places Greece among the countries with very high seismic hazard – the most serious natural threat to the country and its population, as attested by the losses inflicted by earthquakes, both in human and economic terms. (In the last decade or so, forest fires have also caused considerable economic damage, but the majority of these have been attributed to human intervention.)

In the present study we synthesize the experience gained and lessons learned from the study of recent destructive earthquakes, including the Athens tremor of 7 September 1999. We present earthquake and strong-motion data, as well as damage statistics. Causes of typical damages and failure are discussed in relation to the provisions of the various Greek seismic codes. We conclude that although practically no area of Greece can be regarded as seismically safe, seismic risk in Greece can be considered rather moderate. This is attributed, on the one hand, to areas with high population density being exposed to moderate seismic hazard and, on the other, to the generally low vulnerability of structures built according to the provisions of seismic codes, even the oldest one. Thus the faithful implementation of seismic-code provisions, combined with good material and workmanship quality, ensure a reasonable level of seismic risk. A less elaborated version of this paper was presented at the EUROMED-SAFE '99 International Conference, Naples 27-29 October 1999 (Lekidis and Dimitriu[2)]).

2. SEISMIC HAZARD IN GREECE

Greece has by far the highest seismic hazard in Europe and one of the highest in the world (**Fig. 1**). Thus, potentially destructive shallow earthquakes (M_w 5.5 and larger) occur, on the average, as often as one about every 2 months (58 days; **Table 1**). Occurrence statistics for intermediate-depth events are given in **Table 2**. Fortunately, the majority of these earthquakes happen in sparsely populated areas or under the sea, which considerably reduces their destructive capability. Nonetheless, populated areas are affected by damaging to destructive earthquakes quite often, as illustrated in **Table 3**.

The tectonic regime in the wider area is

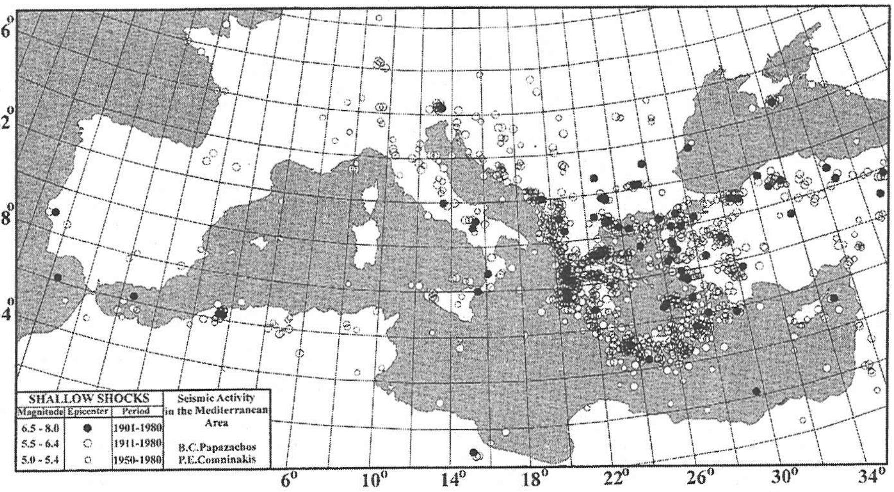

Figure 1 Seismicity of the Mediterranean Sea region and part of Europe (from Papazachos and Papazachou[1]).

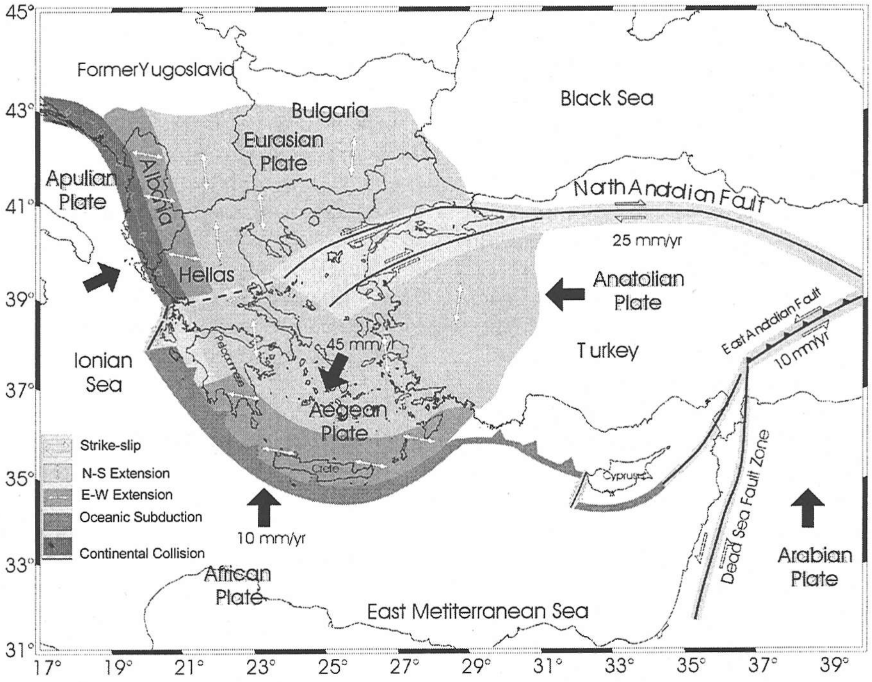

Figure 2 Tectonic setting of the Eastern Mediterranean (from Papazachos and Papazachou[1]).

Table 1 Mean return period, T_m, in years, and mean annual number, N_m, of shallow (h < 60 km) earthquakes with magnitude M_w or larger in Greece and surrounding area (Papazachos and Papazachou[1)])

M_W	5.0	5.5	6.0	6.5	7.0	7.5	8.0
T_m	0.05	0.16	0.5	1.8	5.8	70	850
N_m	20.00	6.25	2.00	0.56	0.17	0.01	0.001

Table 2 Same as Table 1 for intermediate-depth (60 km <= h < 180 km) (Papazachos and Papazachou[1)]).

M_W	5.0	5.5	6.0	6.5	7.0	7.5	8.0
T_m	1	2	5	9	17	32	60
N_m	1.00	0.50	0.20	0.11	0.06	0.03	0.02

Table 3 Mean return period, T_m, in years, and mean annual number, N_m, of earthquakes in Greece that cause damage of maximum intensity I_0 (modified Mercalli scale) or larger (Papazachos and Papazachou[1)]).

I_0	VII	VII+	VIII	VIII+	IX	IX+	X	X+
T_m	0.15	0.32	0.69	1.50	3.24	7.00	15.14	32.73
N_m	6.67	3.13	1.45	0.67	0.31	0.14	0.07	0.03

determined primarily by the convergence, at a rate of about 1 cm/yr, between the Eurasian and African lithospheric plates and by the counter-clock-wise rotation, at about 2.5 cm/yr, of the Anatolian plate relative to Eurasia (**Fig. 2**). The Arabian plate seems to affect the tectonic situation in the area of Greece only indirectly.

3. SEISMIC RISK IN GREECE

(1) Greek Seismic Codes and Categories of Buildings

A summary of the main provisions of the Greek seismic codes follows.

1959 Code. Code based on allowable-stress design. Constant distribution of seismic loads along the height of the structure (building) without overall seismic design. Stress-strain calculation for columns in the building done for each story independently. Ductile frames absent, no ductile provisions whatsoever and nodes designed without stirrups.

1984 Code. Code based on allowable-stress design. Design incorporating ductile frames and concrete shear walls together. Triangular distribution of seismic loads along the height of the building according to the first vibration mode of a regular shear building. Greater detail in the design of joints with increased ductility provisions. Dominant role of capacity design for the stiffness of beams and columns.

1995 Code. Code based on ultimate-strength design. Modern seismic code employing dynamic structural analysis with use of response spectra.

Categories of Greek buildings, built without or according to the provisions of the various codes (since 1959), are presented in **Table 4** and described in greater detail below.

Category-A buildings are generally one- or two-story old (usually over 50 years) houses with load-bearing masonry walls made of stone or brick, weak mortar and usually, but not always, with no seismic provisions such as horizontal concrete or wooden tie-belts. Interior partitions are often made of either low-quality brick or "bagdati" – an old type of wall construction consisting of horizontal wooden planks, 3-4 cm wide, placed in two parallel planes 1-2 cm apart and covered by lime mortar mixed with straw. Floors and roofs are typically wooden, although in more recent constructions reinforced concrete (RC) slabs were sometimes used, providing a diaphragm tying together all load-bearing walls.

The buildings in category B are made of cast-in-place reinforced concrete (RC), with unreinforced hollow-brick walls as partitions, and constitute the majority of residential buildings in Greek cities and towns. Their number of stories varies typically from one to seven, depending upon the area and the height limitations applicable at the time of construction. The load-bearing system, for both horizontal and vertical loads, is a skeleton of columns and beams monolithically supporting the floor slabs. In most cases this system would not qualify as a ductile moment-resisting frame but rather as an irregular space frame whose layout is primarily determined by architectural considerations. A small proportion of these buildings has shear walls, which nonetheless would not qualify as such under current UBC or EC-8 standards. The foundation is usually on spread footings with interconnecting grade beams. A characteristic of this class of buildings that plays a key role in their seismic response is the type of the ground story. Some time in the 70's, the General Greek Building Code permitted, and the authorities encouraged, the construction of an open ground story, called "pilotis", for car parks, flowerbeds, playgrounds, etc., without counting it in the maximum allowable total floor area.

"Pilotis" became very popular, but created a "soft" first story as a result of the drastic reduction

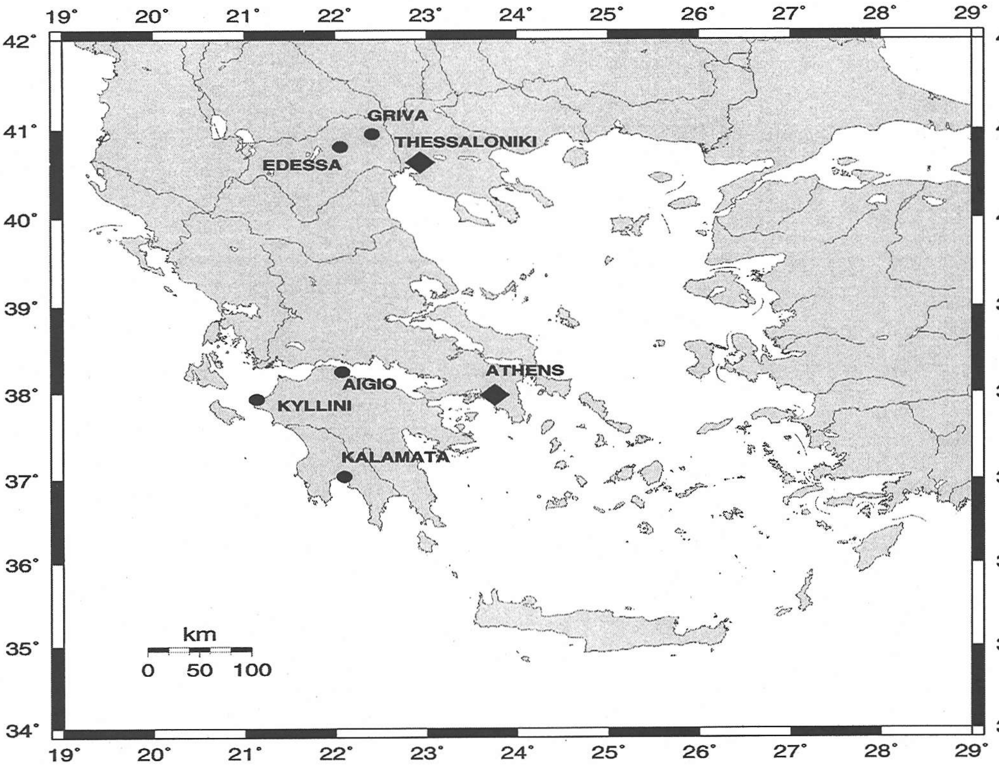

Figure 3 Map of Greece and surrounding areas showing Greek cities and villages where damage due to recent earthquakes is analysed in the present study.

of brick infills in comparison with the stories above. A similar – though less severe problem – is caused by ground stories used as shops (removal of infill walls to create open spaces and front windows).

Class C comprises RC structures – with comparatively large plan dimensions – used for industrial or commercial operations, schools, etc. Their number is only a small fraction of the buildings in categories A and B. The load-bearing system of such structures – typically one- or two-story high – usually consists of well-defined moment-resisting frames, though without the ductility levels required by the modern seismic codes. The great majority of the existing buildings in categories B and C were designed with the 1959 Seismic Code.

Buildings in Class D are historic (ancient or Byzantine) special-purpose structures (temples, theatres, churches, monasteries, etc.), usually showing very good seismic behaviour, attested by their history, thanks to a number of factors. Among the most important of these are the bulky design (structural elements), good materials (e.g. marble) and workmanship quality and often the choice of their location (usually on rock outcrop or firm ground). These edifices survived the strong earthquakes of the last three decades, usually with little or no damage.

(2) Case studies

Here we summarize the effects of four recent earthquakes on the buildings of four Greek cities (Kalamata, Edessa, Aigio and Athens) and two villages (Kyllini and Vartholomio) and attempt to draw conclusions regarding their seismic performance (vulnerability) (**Fig. 3**). The presentation concerning these events generalizes the results of two previous studies by Lekidis et al.[3),4)], which can be addressed for details. The Athens earthquake, because of its importance, is considered separately, at the end of each section;

relevant references include the ITSAK web site (www.itsak.gr), Andrianakis et al.[5], Papadopoulos et al.[6], Anastasiadis et al[7].

a) Earthquakes and strong-motion data

Relevant earthquake and strong-motion data for the events studied are summarized in **Table 5**. All available mainshock recordings are analog (corrected) accelerograms, recorded by instruments of the permanent national strong-motion network. The accelerographs are located in or close to the administrative-commercial centres of the respective cities, except in the case of the Kyllini earthquake, where the recording of the town of Zakinthos (about 20 km from Kyllini and 12 km from the epicentre) is used.

On 7 September 1999, at 14:56 local time (11:56 GMT), a strong earthquake with moment magnitude M_w 5.9 occurred in the vicinity of the capital of Greece Athens. The current best estimate of the hypocentre location is 38.06°N, 23.57°E, with focal depth 15 km. The fault-plane solution by Harvard University indicates a WNW-ESE trending, almost south-dipping normal fault.

The tremor caused the collapse of 65 buildings, all but a few residential, claiming 143 lives and injuring some 7,000. (The death toll would have been considerably higher had the earthquake occurred late in the evening or at night.) More than 70,000 families became homeless. The most extensive and severe damage occurred in the northern suburbs of Athens (~1,000,000 inhabitants), located northeast of the epicentre, in the meizoseismal area, apparently in the direction of the fault rupture. The dominant construction systems in these suburbs are reinforced concrete frames and one or two-story buildings with masonry walls. Most of the structures were built to the (outdated) 1959 Seismic Code; a significant number of mainly residential buildings were built illegally, i.e. without fulfilling code provisions.

The quake inflicted severe damage upon several northern suburbs of Athens in the near-fault area, where estimates indicate a Modified-Mercalli (MM) intensity from VI to IX. All three analog SMA-1 accelerographs operated at the time by the Institute of Engineering Seismology and Earthquake Engineering (ITSAK) in the city of Athens recorded the mainshock (**Fig. 4**) and many of the aftershocks. Within a few days after the main event, ITSAK staff deployed another six digital accelerographs in the meisoseismal area close to major collapses, where its engineers carried out a preliminary damage survey. Moreover, a mobile multi-channel recording unit was also installed and operated in a public building in the Thracomakedones district.

Upon a first comparison, the Athens earthquake appears to have been less severe than most of the tremors that hit major urban areas in Greece (**Table 6**). But one must keep in mind that the highest PGA unaffected by topography or other effects (0.3g, corrected value) was recorded outside the meizoseismal area, at an epicentral distance R≈11 km (record ATH03, **Fig. 4**). (Experts agree that the value 0.5g recorded at Monastiraki is largely due to the vicinity of a construction site; e.g. see Papadopoulos et al.[6]). Within the meizoseismal area (R<=5 km), PGAs may have been as high as, or even in excess of, 0.5g, especially considering near-fault and directivity effects, which apparently were significant. Thus, the fault geometry and strong-motion modeling suggest bilateral rupture propagation with the upgoing branch directed toward the western suburbs of Athens (ITSAK report[8]). Moreover, the widespread expulsion of burial plates and buried coffins in the Fili-village cemetery indicates that vertical accelerations may have locally exceeded 1g, although there are experimental and numerical data attributing the upthrow of objects to their nonlinear dynamic interaction with the ground (e.g. Ohmachi and Midorikawa[9]).

b) Ductility demands

The accelerograms (the strongest horizontal components, see **Table 5**) of the first four events were used to compute the elastic response spectra and compare them with code provisions. At the time of the corresponding earthquakes, the great majority of the buildings in the affected populated areas were built to the 1959 Seismic Code. According to this code, based on the allowable-stress design method, for the areas of Kalamata, Kyllini and Aigio the (design) base-shear coefficient is ε = 6%, 8% and 12% of the total weight for stiff, intermediate and soft soils, respectively. For Edessa, the corresponding values of the coefficient are 4%, 6% and 8%. In the 1959 Code, the base shear coefficient is assumed constant, independent of the building's natural period (i.e. number of stories).

To assess the ductility demands, q, imposed by the earthquakes on the buildings of Kalamata, Kyllini, Edessa and Aigio, the normalized peak values of the elastic response spectra, Sa, are compared with the corresponding ultimate-strength design base-shear coefficients, ε' ($q=Sa/\varepsilon'$). q is called the inelastic-behaviour coefficient and is

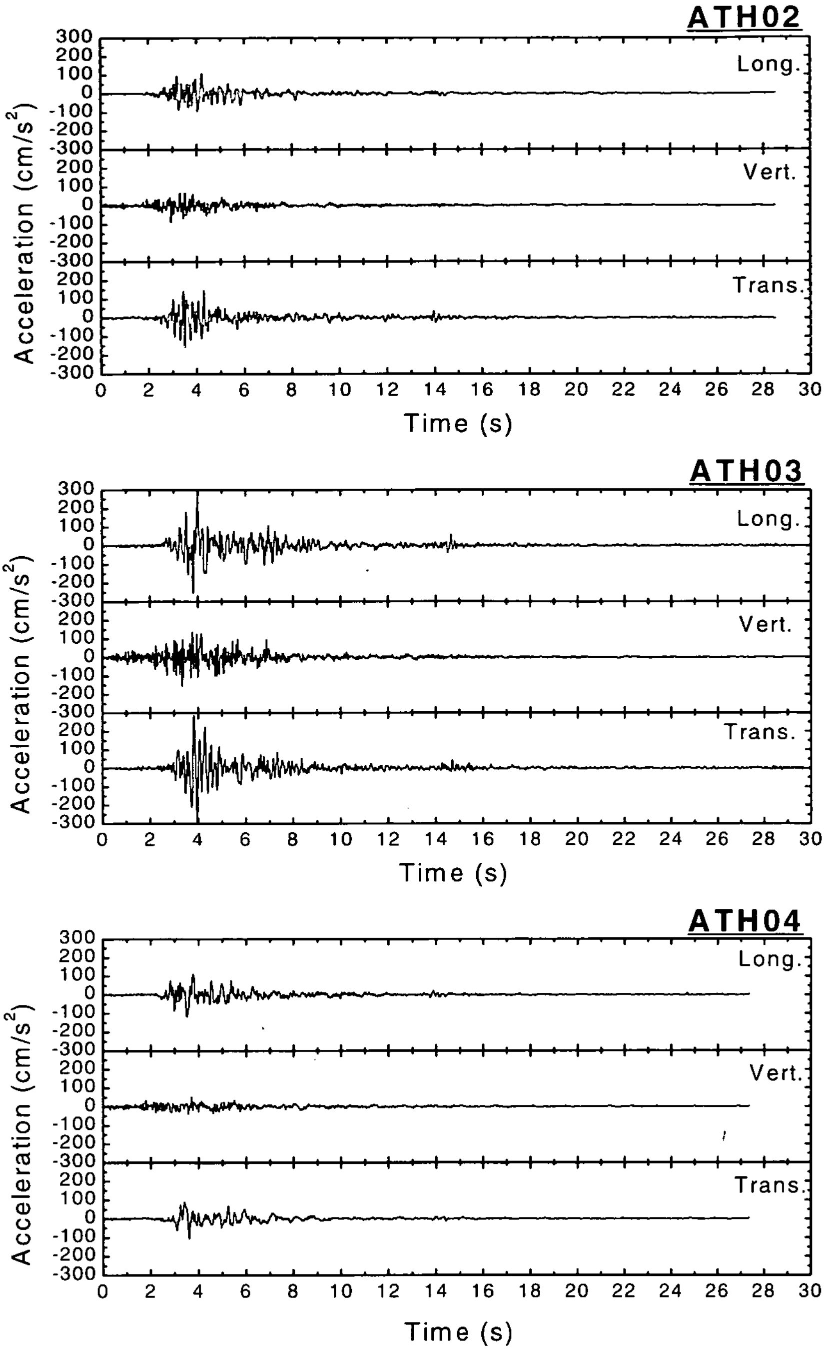

Figure 4 Corrected accelerograms of the 7 September 1999 (M_w 5.9) Athens earthquake recorded by the stations of the ITSAK permanent network.

Table 4 Typical buildings in Greek urban and rural areas (about 80-90% of the total). Historic structures are in a separate class (D).

Category	Description	Remarks
A	One- or two-storey buildings with masonry bearing walls	Mostly old residential buildings and shops. Walls made of stones or hollow bricks with mortar based on lime and more rarely on cement or mud. Typically *without any seismic provisions*, except for a small percentage that may have wooden or concrete tie-belts.
B	Modern reinforced concrete (RC) buildings with one to seven stories	Mostly residential or office buildings made of cast-in-place reinforced concrete. A skeleton of columns and beams monolithically supporting floor slabs forms the load bearing system. Unreinforced, hollow brick walls used as infills. Most of buildings designed in accordance with the *1959 seismic code.*
C	Special reinforced concrete buildings	Usually buildings with large plan dimension for commercial or industrial use, schools, etc. Some with steel roofs. Most of them designed in accordance with the *1959 code.*
D	Historic buildings and monuments	Buildings belonging to the historic architectural heritage (ancient and Byzantine monuments, churches, etc.), typically built with specific materials (e.g. marble).

Table 5 Relevant earthquake and strong-motion data. R is epicentral distance to the recording stations and I_0 is the maximum estimated MM intensity in the affected populated areas, namely Kalamata, Kyllini, Edessa, Aigio and Athens.

Event	Date	Coordinates		M_w	Mechanism	R (km)	PGA (cm/s/s)			I_0 (MM)
		ºN	ºE				L	V	T	
Kalamata	13/09/86	37.05	22.11	6.0	Normal	9	235	178	268	IX
Kyllini	16/10/88	37.91	21.06	6.0	Str-Slip	17	125	69	167	VIII
Griva	21/12/90	40.92	22.36	6.0	Normal	31	100	40	96	VII
Aigio	15/06/95	38.36	22.22	6.4	Normal	18	493	193	537	VIII
Athens	07/09/99	38.06	23.57	5.9	Normal	11	259	154	297	IX

also referred to as the response-modification factor in the UBC code; ε' is obtained from the base-shear coefficient, ε, derived by the allowable-design method (e.g., Lekidis et al.[4]). Comparison of the ductility demands with ehat is estimated to be the available ductility reserves of the buildings provided by the code in force show that, in all four cases,the former exceeded the latter. As exemplified by the case of Aigio, even the provisions of the New Greek Seismic Code of 1995 (design spectrum for intermediate soil conditions) were surpassed by the shaking, especially in the critical period range, 0.2-0.6 s (Lekidis et al.[4], **Fig. 11**).

In Athens and its suburbs, the great majority of buildings were designed for a seismic force of 4%, 6% or 8% of the weight for firm, intermediate and soft soils, respectively (1959 Code). The same procedure as above was used to assess the ductility demands imposed by the tremor on the buildings of Athens and surroundings. Again, as for the earthquakes considered previously, the ductility demands exceeded the ductility reserves provided by the 1959 code in the critical period range. The tremor, as revealed by the response spectra of the recorded motion (**Fig. 5**), had the strongest effect on low to mid-rise buildings (two to four stories). In this period range (0.2 – 0.4 s), the shaking intensity considerably surpassed the provisions of even the more conservative New Greek Seismic Code (NEAK), based on ultimate-strength design. At periods corresponding to buildings with more stories (T>0.4 s), spectral accelerations show a rapid decrease, implying a corresponding diminishing effect.

c) Damage statistics

Earthquake-induced structural damage in Greece is classified according to the Damage and Usability State of Buildings classification, including three categories (**Table 6**). It must be pointed out that in spite of numerous efforts there is no generally accepted damage-classification system (e.g., Pomonis et al.[10]; Spencer et al.[11]). The main reason is the objective difficulty to quantify damage (its extent and severity), rendering all classification systems rather qualitative and hence liable to considerable subjective bias. The results of the damage surveys carried out in the cities of Kalamata, Edessa and Aigio and the villages of Kyllini and Vartholomio are summarized in **Figure 6**. The great majority of the buildings in Kalamata belong to categories A and B (see **Table 4**); 205 traditional buildings were thoroughly inspected, and the damage statistics are reliable.

It must be pointed out that because no questionnaires were used in Kyllini and Vartholomio, damage statistics here are less complete and coherent compared with the other study cases.

It is interesting to note that, as far as "red" buildings are concerned, damage in Edessa was by comparison rather severe. Site effects (soil quality and topography) and the large number of old houses in the historic part of the city seem to be responsible.

Remarkable is the trend toward decreasing damage from the Kalamata and Edessa events to Aigio (top plot in **Fig. 6**), even though the Aigio earthquake generated the strongest ground motion ever recorded in Greece (see **Tables 5** and **7**). As illustrated in the corresponding plot in **Figure 6** (second from bottom), the application of the 1984 code proved extremely beneficial for the seismic safety of buildings. Furthermore, in Kalamata and Edessa there were numerous old, non-RC buildings that suffered severely from the earthquakes.

In the three cities the distribution of damage was quite non-uniform. Thus in Aigio the damage was mainly concentrated along a strip approximately parallel to the coastline (Gazetas et al.[12]), decreasing – in degree and density – very abruptly in the southward direction, i.e. away from the epicentre. Strong-motion intensity apparently decreased much faster westwards than eastwards.

The typical building stock in the northern suburbs of Athens mainly consists of RC low and mid-rise (2 – 5 stories) buildings, the majority of which were built to the 1959 Code (without ductility provisions), or, even worse, were illegally built and of poor construction, without conforming even with the minimal requirements of the 1959 Code. This, combined with the indisputable severity of shaking and certain design and construction deficiencies, explains the severity and extent of the damage, including the great majority of the 65 collapses. In the municipalities of Ano Liosia, Aharnes, Philadelphia, Metamorfosi and Thrakomakedones there were several collapses of mid- and high-rise buildings built to the revised 1984 Code.

Because of the hour (14:56), the greatest number of the deaths occurred under the ruins of three industrial buildings. These facilities were constructed on the crest of the west bank of the Kifissos river (Chelidonou stream), which apparently greatly amplified shaking (site effects). In the municipality of Menidi, around the town hall, one could observe typical damage patterns

Table 6 Damage and Usability of Buildings classification adopted in Greece.

Category	Colour	Description
I	Green	Original seismic capacity little impaired, buildings immediately usable with unrestricted entry
II	Yellow	Impaired seismic capacity, need for repair work, permanent usage prohibited
III	Red	Buildings unsafe and entry prohibited; decision on demolition upon further thorough inspection

Table 7 Comparison of recent, damaging normal-faulting earthquakes in Greece.

Location	Date	M_w	R km	PGA g	PGV cm/s	PGD Cm	PGV/PGA cm/s/g	BD* s	EPA** g	SCZ*** Zone- g
Thessaloniki	20/6/78	6.4	29	0.15	16.7	3.4	111	6	0.13	II - 0.16
Corinthos	24/2/81	6.6	30	0.29	24.6	6.7	85	11	0.24	III - 0.24
Kalamata	13/9/86	6.0	12	0.27	32.3	7.2	120	4	0.28	III - 0.24
Kozani	13/5/95	6.6	19	0.21	8.8	1.5	42	7	0.14	I - 0.12
Aigio	15/6/95	6.4	18	0.54	51.7	7.5	96	6	0.43	III - 0.24
Athens-02	07/9/99	5.9	13	0.16	6.9	1.0	46	2	0.14	II - 0.16
Athens-03			11	0.30	16.1	2.1	61	5.5	0.25	II - 0.16
Athens-04			16	0.12	8.9	1.7	77	4	0.11	II - 0.16

(*) Bracketed duration: time interval between the first and last acceleration peak >= 0.05g.
(**) Effective peak acceleration after FEMA (1985)
(***) 1995 Seismic Code Zone – proposed effective acceleration

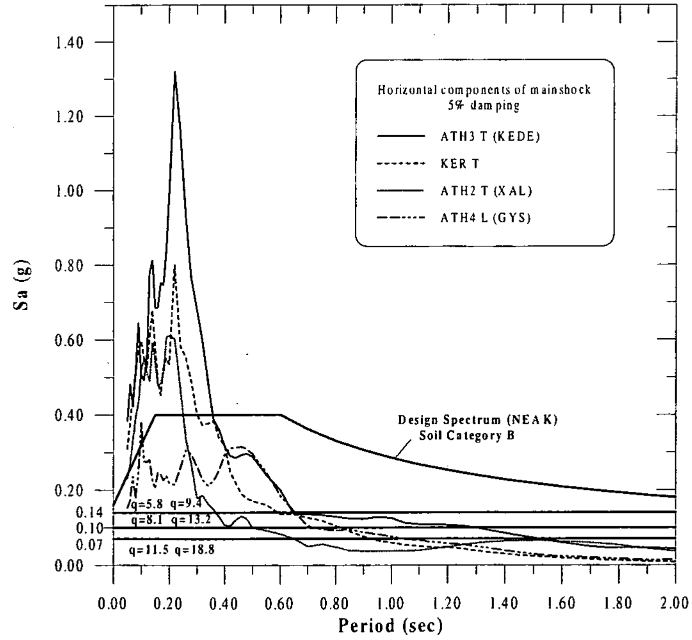

Figure 5 Acceleration response spectra (largest horizontal components) of the 7 September 1999 Athens earthquake and comparison with elastic design spectrum of the 1995 Greek Seismic Code and the seismic (base-shear) coefficient of the 1984 Code. For each of the three values of the coefficient, corresponding to three soil categories, there are two values of the inelastic-behaviour coefficient, q, one for each period range considered: 0-0.15 s and 0.15-0.3 s.

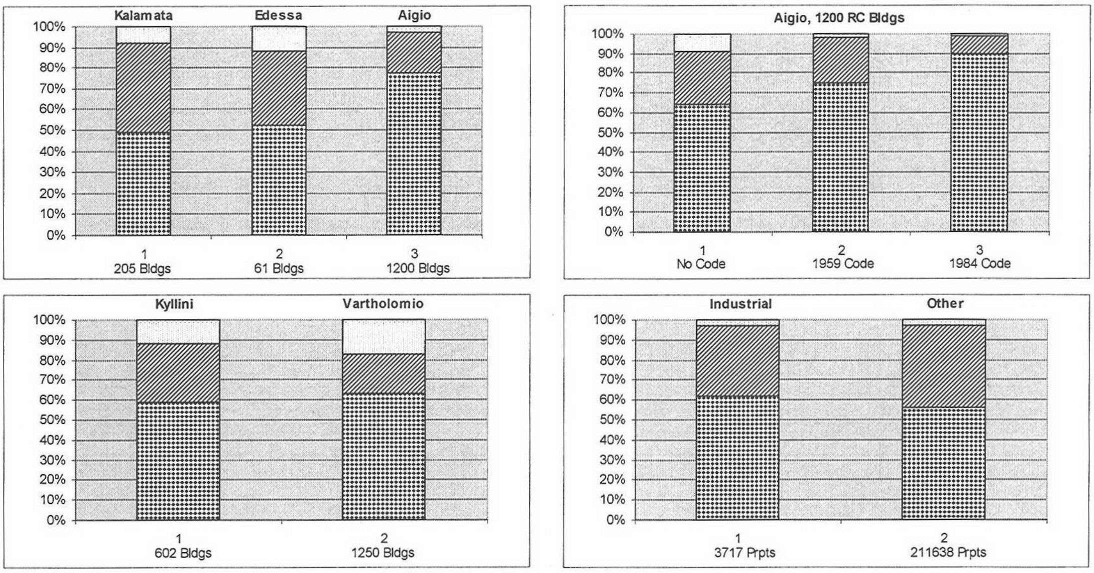

Figure 6 Damage statistics of buildings and properties in the cities of Kalamata, Edessa, Aigio and Athens (right-bottom plot; see **Table 8**) and the villages of Kyllini and Vartholomio using the "Green-Yellow-Red" (bottom to top) classification (see text).

sustained by RC buildings, including several collapses and total failures of concrete frames. Buildings in the Thrakomakedones district – a district with independent one- and two-story houses – performed comparatively better than elsewhere.

Industrial buildings in the hardest-hit areas suffered severe damage, and there were several collapses (RICOMEX, FOURLIS, FARAN, etc.). Serious damage causing disruption of operation was inflicted on several hospitals, particularly those of Voula, Nikea and Sotiria; milder damage occurred in another 27 hospitals. About 150 school buildings in Attica suffered non-structural damage that, nonetheless, caused interruption of their operation. Several schools suffered more severe damage that could be repaired, however. In addition, 80-day nurseries belonging to the Health and Welfare Ministry suffered seriously, with another 18 requiring demolition.

The earthquake also affected monuments. Severely damaged were Dafny Monastery (11th century), the Fortress of Fili (5th century BC), the wall of Elefsina (5th century BC). Seriously affected were also a large number of engineered buildings housing cultural activities or objects of cultural value, including the National Theatre, the National Opera and the Archaeological Museum.

The overall damage picture in the meizoseismal area is very similar to what had been observed in previous earthquakes in Greece. Typical examples include: (1) damaged columns and failures at joints in buildings with "pilotis" (**Photo 1**); (2) damage due to lack of shear walls, particularly around staircases; (3) shear failures of short columns (**Photo 2**); (4) damage due to lack of stirrups in columns. Also, concrete in Ano Liosia was apparently of lower quality than elsewhere. Furthermore, a number of adjacent buildings suffered because of pounding (**Photo 3**). The overall performance of new buildings (1984 and 1995 Codes) was rather satisfactory. A summary of the second-level inspection results for the broader metropolitan area of Athens is presented in **Table 8**, where the buildings were categorized and marked according to their state following the standard "green-yellow-red" classification (see above).

Lifelines behaved generally well. No major damages were reported for water, sewage, telecommunication, gas and electricity networks. Bridges and highway overpasses were relatively unharmed, and vehicle circulation was in general problem-free. The most serious problem occurred on a highway overpass in Aspropyrgos (in the

Table 8 Results of second-level seismic inspection of broader Athens metropolitan area (see **Fig. 6**, bottom plot). See **Table 6** for description of the three damage categories, "green", "yellow" and "red".

	Bldgs	Apart-ments	Commercial	Total Properties	Green	Yellow	Red
Industrial	1325	175	3542	3717	2324 62.5%	1294 34.8%	99 2.7%
Other property	62650	186940	24698	211638	118391 *55.9%*	87100 *41.2%*	6147 *2.9%*

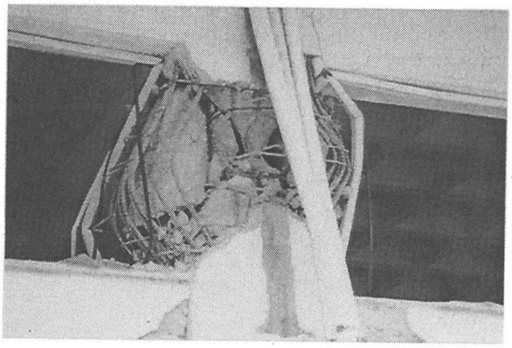

Photo 1 3-story RC building with pilotis, Ano Liosia.

Photo 3 Damage due to pounding, Menidi.

Photo 2 Column failure, due to the short-column effect, in a 5-story building in Ano Liosia.

epicentral area), on the Athens-Korinthos highway. Damage of the brick cladding around the elastomeric bearings of the piers led local authorities to halt circulation, causing a severe traffic jam, aggravated by citizens trying to flee the city. Circulation was resumed about five hours after the event. Noteworthy is the failure of telecommunication networks, permanent and mobile alike, to manage the increased number of calls in the first 36 to 48 hours following the tremor.

4. DISCUSSION AND CONCLUSIONS

As demonstrated by recent earthquakes, practically no urban or other area in Greece can be considered aseismic (i.e. exposed to negligible seismic hazard). The tectonic evolution of this part of the Eastern Mediterranean renders very likely the presence of faults in the proximity of urban/populated areas. Even though some of these faults may have been inactive in recent geologic times (most of the faults in Greece are anyway hidden, i.e. without notable surface expression), one cannot – and should not – rule out the possibility of their generating potentially damaging tremors in the future. The 1995 Kozani-Grevena (M_w 6.6) and Griva earthquakes, which occurred in areas previously regarded as aseismic, the Aigio event, which produced unexpectedly high accelerations (the highest ever recorded in Greece), as well as the most recent Athens tremor, which ruptured a previously unmapped fault, support the above observation.

On the other hand, historic, economic and social factors, in combination with the country's landscape (most of the area is covered by high mountains and sea), have contributed to a geographically extremely uneven exposure to seismic hazard. Thus more than half of Greece's over 10 million population (and hence industry and infrastructure) is concentrated in and around two large urban conglomerates, Athens (over 4 million) and Thessaloniki (over 1 million), leaving large areas almost unpopulated or sparsely populated.

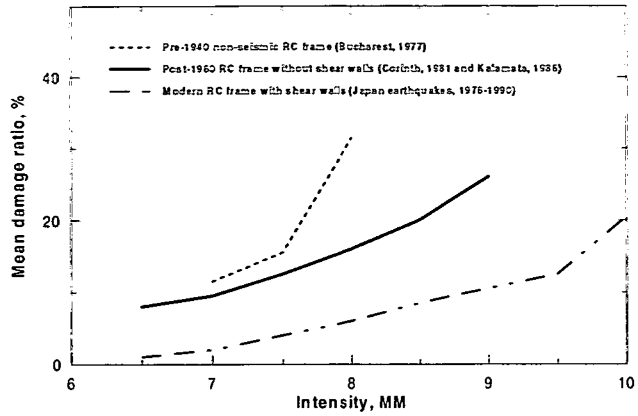

Figure 7 Comparative performance of RC buildings in Greece, Romania and Japan, in terms of mean damage ratio. Adapted from Pomonis and Spence, 1995. This figure illustrates the beneficial effect of seismic code implementation and upgrading, from the non-seismic buildings in Bucharest (RC beams laying on RC columns – so-called "skeleton" system) to the Greek 1959-code buildings (RC frames without adequate ductility) to the more modern Japanese RC frames with high ductility provisions.

The strongly uneven spatial distribution of damage, often observed even within small areas with similar type of buildings (e.g. the cases of Kalamata and Edessa, where any two points are less than 3 km apart), implies large spatial variations of ground shaking. These variations can be attributed to source effects (mechanism and directivity, e.g., Kalamata and Aigio), site effects (e.g., Edessa) or a combination of both (e.g., Athens). On the other hand, the recent earthquakes clearly demonstrated the increased safety provided by the seismic codes, especially the more recent ones (e.g. **Fig. 6**, top right plot). Thus the overall situation must have improved compared to the one described in the study by Pomonis and Spence[13] (**Fig. 7**).

It is important to note that the relationship between the number of earthquake casualties (deaths and injuries) and vulnerability is a complex one. For example, two critical factors greatly affecting the number of casualties are the time of occurrence of an earthquake and the occurrence or not of foreshocks. In Greece, in spite of the decrease in the vulnerability of structures in the last few decades, the number of casualties is almost stable.

The main conclusions follow.

Seismic Hazard is high almost everywhere in Greece. On a short to intermediate time scale (<= 50 years), hazard is largely determined by earthquakes with 5.5 <= M_w <= 7.0 at epicentral distances R <= 20 – 40 km. On longer time scales (100 – 1000 years), shocks as big as M_w8 or even greater may occur. The most likely location of such plate-rupturing events is the outer part of the Hellenic arc, at the contact between the African and Aegean plates (**Fig. 2**), with the potential of affecting even remote areas in the Eastern Mediterranean (e.g., the earthquake with estimated magnitude 8.3 in 365 AD; Papazachos and Papazachou[1], p. 182).

Source location (sea or land), source parameters (mechanism, directivity, depth), attenuation of ground motion and site conditions are all important factors affecting seismic hazard.

Exposure to seismic hazard is very uneven: about 60% of the population and hence most of the dwellings, industry and infrastructure are concentrated in and around the two largest cities, Athens and Thessaloniki.

Vulnerability is crucial. Below we list the categories of buildings in order of year of construction and decreasing vulnerability:

- built without code provisions (before 1959 or without authorities' permission)
- built between 1959 and 1984 (1959 Code; since 1970s "pilotis")
- built after 1984 (Revised Code)
- built after 1995 (New Greek Seismic Code)

Common design/construction *problems/ malpractices* enhancing vulnerability are:

- sites with poor soils (reclaimed land, river/stream beds, etc.) or irregular topography (hills or abrupt river banks)

- unauthorized removal of infill walls (or even columns!) to increase usable area
- pilotis without shear walls along perimeter
- insufficient shear walls
- short columns, especially on basement and ground levels
- staircases without strong cores
- adjacent buildings with unequal number of stories
- inclined footing, nonuniform basements
- nonuniform distribution of stiffness and mass
- heating/cooling and drainage systems in load-bearing elements

Overall behaviour of the building stock satisfactory: infill walls, good material and workmanship quality in combination with adequate code provisions ensure over-strength and redundancy.

Pre-seismic inspection and – where needed – strengthening of structural elements can substantially reduce their vulnerability.

ACKNOWLEDGEMENTS: This study would have been impossible without the contribution of ITSAK's scientific and technical staff: being responsible for the national strong-motion network, they collected and processed the strong-motion data and participated in damage surveys and in the elaboration of the 1995 New Greek Seismic Code. We thank Ioannis Kalogeras and the Geodynamic Institute of the National Observatory of Athens (GI-NOA) for providing the recording of the Aigio earthquake. Christos Papaioannou prepared Figures 2 and 3.

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(Received May 7, 2001)