Natural Hazards **18:** 237–251, 1999.

Seismic Hazard Assessment in the Area of Mystras-Sparta, South Peloponnesus, Greece, Based on Local Seismotectonic, Seismic, Geologic Information and on Different Models of Rupture Propagation

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(Received: 12 December 1997; in final form: 30 September 1998)

Abstract. Strong seismic events once again confirm the view that great destructive earthquakes are produced by the reactivation of pre-existing faults although they have usually remained inactive for many, perhaps thousands of years. It is evident that such active seismogenic zones, with little or no seismicity, have presumably been ignored in the determination of the region's seismic hazard.

At south Peloponnesus, Greece, is situated at Taygetos mountain. At its eastern front lies a large normal fault system, the southern segment being the Sparta fault. This area has been characterized by low seismicity for the last 25 centuries. However, during the 6th and 5th centuries B.C. several destructive earthquakes have been reported. That of 464 B.C., was the most destructive and devastated the city of Sparta. Detailed morphotectonic observations of this area, suggest that the earthquake of 464 B.C. could be related to the most recent reactivation of this fault.

The ground accelerations that would be produced by a future activation of the Sparta fault, were calculated, by applying a method which takes into account information mainly from the seismotectonic parameters of the Sparta fault, the rupture pattern, the properties of the propagation medium and the local ground conditions. Moreover, these results were compared with those of other independent studies based mainly on the seismic data of the area. This method estimated greater expected values of ground acceleration than those computed by the conventional seismic hazard methods. The highest values correspond to the activation of the Sparta fault either in a unilateral rupture, which would start from the southernmost point of the fault, or in a circular one. Furthermore, an increase is observed of the order of 50% in the ground acceleration values in unconsolidated soft ground in relation to the corresponding values of hard ground.

Key words: active fault, seismotectonics, rupture pattern, seismic hazard assessment, Greece.

Subject Index: E1: seismic motion, seismotectonics, 3.4 hazard assessment.

1. Introduction

Seismic hazard is a measure of earthquake ground shaking and is defined as the probability of occurrence of a certain level of ground motion in a specified time period at a given location. The assessment of seismic hazard depends upon our understanding of how earthquakes are generated and distributed and of how they recur in space and time. Two approaches are usually used for seismic hazard assessment at a regional scale: the historical method which, by using an extreme value distribution, attempts to extrapolate the patterns of past seismicity (location in space and time, frequency-size distribution) to long time periods and the time-dependent approach which utilizes non-Poissonian statistics to incorporate the memory of past events in the probabilistic scheme, so that fault zones that ruptured in recent large earthquakes become less hazardous than others that did not rupture in recent history.

Catastrophic seismic events which occurred in recent decades at different places of the world (Armenia, San Francisco, Los Angeles, Kobe, Greece) confirm once again the view that great destructive earthquakes are produced by the reactivation of pre-existing faults although they usually exhibit a peculiar behavior by staying inactive for many, perhaps thousands of years (Stein and Yeats, 1989; Philip *et al.*, 1992; Sieh *et al.*, 1992; Dolam *et al.*, 1995; Yeats and Huftile, 1995; Tsutsumi and Okada, 1996; Papanastassiou *et al.*, 1998). It is evident that such active seismogenic zones, with little or no seismicity, have presumably been ignored in the determination of a region's seismic hazard. Therefore, the application of such methods, based primarily on the known seismic history of that region, may produce to unreal results.

The modern city of Sparta, south Peloponnesus, is built on the same site where the famous ancient city which flourished from classical to Roman times, stood. The Byzantine city of Mystras is located 5 km to the west (Figure 1). The castle and the fortified city of Mystras were built in the 13th century and became the center of civilization of the last dynasty of Byzantine Emperors. This area has been characterized by low seismicity for the last 25 centuries. However, several destructive earthquakes have been reported during the 6th and 5th centuries B.C. (Guidoboni *et al.*, 1994; Papazachos and Papazachou, 1997). That of 464 B.C., was the most destructive and devastated the city of Sparta. West of Sparta lies the Taygetos mountain front. At its base the Sparta fault is located (Figure 2). The Byzantine city of Mystras is built on the northern end of this fault. Morphotectonic study of the fault suggested that the earthquake of 464 B.C. should be related with the most recent reactivation of this fault.

It is obvious that the Mystras–Sparta area in spite of its low seismicity, is under threat of a future reactivation of the Sparta fault. To resolve this hazard assessment problem and to obtain more realistic results other methods should be applied, incorporating the seismotectonic characteristics of the seismogenic zones with different scenarios and models of rupture of strong earthquakes. It is accepted that a relation exists between near field ground motion and the nature of the field rupture, while the severity of strong motion in the near field plays a predominant role in earthquake damage.

Figure 1. Location of the study area in Greece.

For the evaluation of the earthquake hazard of the area of Mystras, information from the seismicity of the area and the local seismotectonic and geologic regime have been used. Different scenarios and models of rupture of strong earthquakes have been tested, in order to simulate the destruction caused by the activation of this fault and assess the seismic hazard of a future reactivation. The results were evaluated and compared with those of other independent studies using different approaches to seismic hazard evaluation.

2. Local Geologic – Tectonic Conditions

Sparta is located in the Eurotas valley, which comprises an asymmetric depression bounded by the mountain masses of Parnonas (1935 m) in the east and Taygetos (2407 m) in the west. The valley is filled by Plio-Pleistocene terrestrial and lacustrine sediments derived primarily from Parnonas. These are overlain only in the west of the depression by the more recent Taygetos deposits (Figure 3).

Mystras is built on a small hill (632 m), at the northern end of the Sparta fault. The configuration of the Mystras hill is mainly due to erosion and tectonism. An important factor in the configuration of the hill was the lithology which is mainly fragmented and the low resistance limestones, scree and unconsolidated deposits. The erodable and impermeable phyllitic basement is located around or at the base of the hill. The limestones present a more rugged topography with cliffs

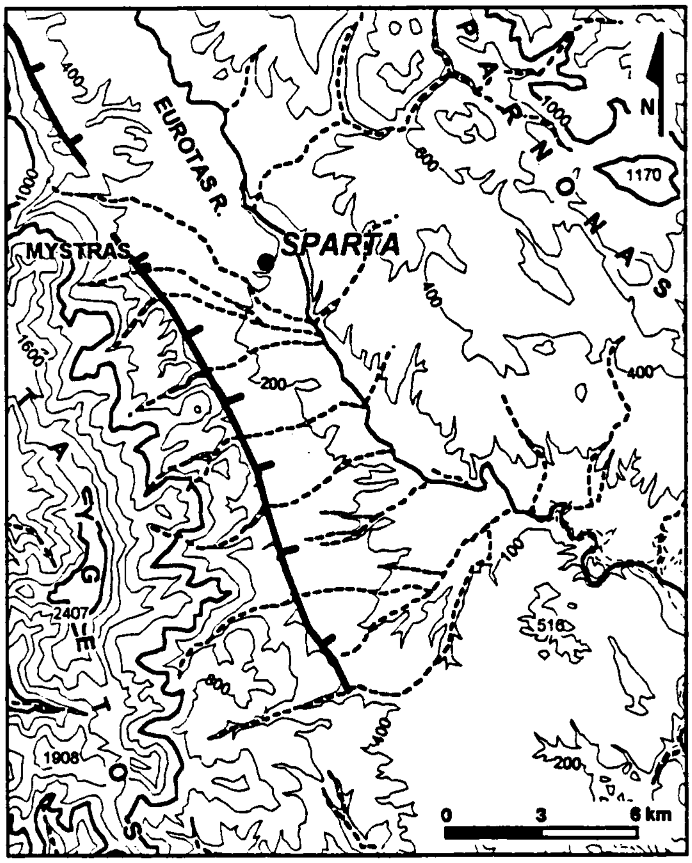

Figure 2. Location of Mystras and Sparta in relation to the Sparta fault.

and steep slopes. Noteworthy is the presence of four morphologic levels which have been artificially filled and leveled broadening their area. The phyllites and scree-unconsolidated deposits present a more gentle terrain.

The main tectonic feature of the hill is the Sparta fault, with characteristic appearances of the fault mirror. Apart from these, fissures and joints were also observed having directions parallel or perpendicular to the main fault.

3. Morphotectonic Observations

The eastern front of the Taygetos mountain constitutes, morphotectonically, one of the most impressive normal fault systems in Greece (Armijo *et al.*, 1991; Gaki-Papanastassiou *et al.*, 1996). It has a length of 60 K m, direction NNW–SSE, dips towards the east and consists of several segments. The southern one is the Sparta fault. It has a direction of N30°W, a length of 20 Km and a dip of 40° towards the east. At the base of this front a fault scarp is observed (the Sparta fault) the middle

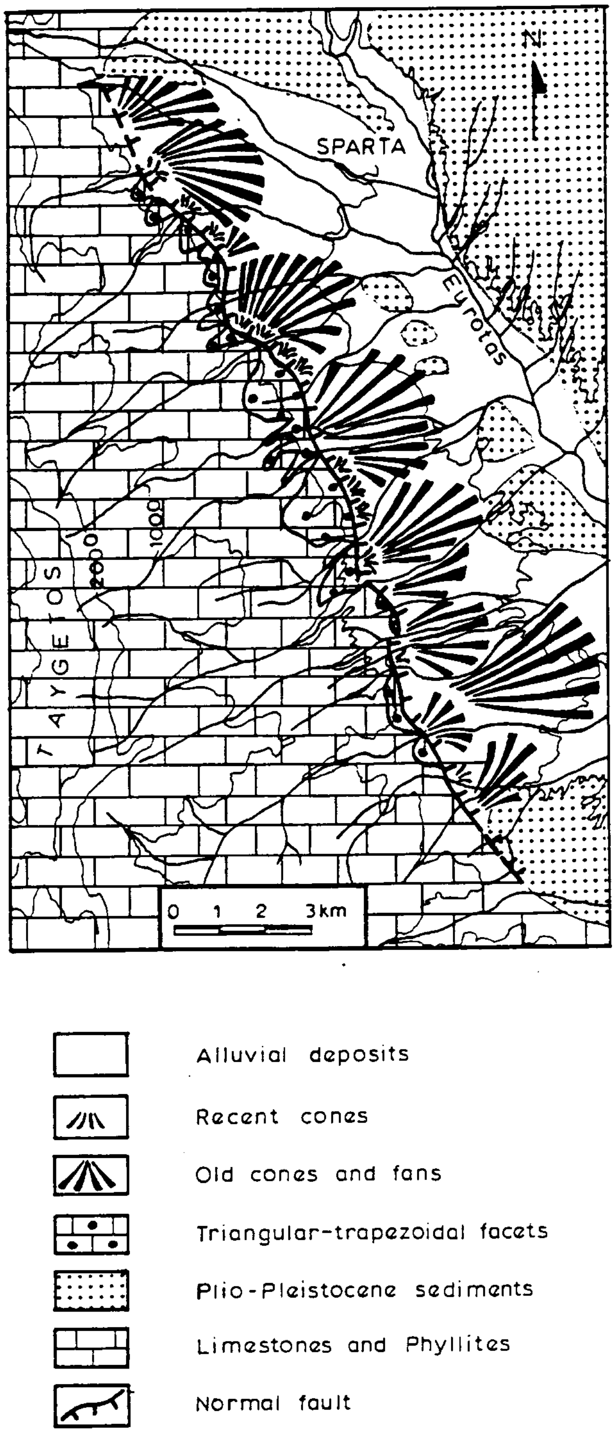

Figure 3. Morphotectonic map of the Sparta fault.

section of which reaches to heights of 12 m. Furthermore, the front is traversed by deep gorges, the longitudinal profiles of the torrents issuing from the Taygetos have steep gradients and at their exit from the mountain, most of them exhibit high knickpoints up to 6 m. In the space between the torrents, triangular and trapezoidal facets have formed, while at the base of the front, steep talus slopes are observed. East of the Taygetos, multi-generation alluvial fans reach as far as the Eurotas river (Figure 3). In many locations along the fault plane, the remains of tectonic breccia are still visible while at others the fault has truncated old, consolidated scree material which in the form of prisms comes into direct contact with the fault plane.

All the above constitute morphotectonic features that advocate recent reactivation of this fault.

4. Seismicity of the Area

The historic seismicity of this region is characterized as low. However, it has not always been so quiet (Galanopoulos, 1961; Guidoboni *et al.*, 1994; Papazachos and Papazachou, 1997). During the 6th and 5th centuries B.C. several destructive earthquakes have been reported by historians, like those of 550, 496, 464 and 412 B.C.. Among them, that of 464 B.C. was the most destructive and devastated the city of Sparta, killing more than 20 000 people and causing great social upheaval. Armijo *et al.* (1991), after a detailed morphotectonic study of the eastern Taygetos front, maintain that this earthquake should be related to the most recent reactivation of the Sparta fault, which means that the recurrence interval for strong earthquakes for this fault is more than 2500 years.

The instrumental seismicity of this area is also low (Galanopoulos, 1960; Comninakis and Papazachos, 1986; Makropoulos *et al.*, 1989; Papazachos and Papazachou, 1997; monthly Bulletins of the Institute of Geodynamics of the National Observatory of Athens) (Figure 4). In the present century, several tens of earthquakes were felt in the Mystras–Sparta area. Most of them were just felt, had a short duration and low intensity of IV–V degrees on the Modified Mercalli (MM) scale. There were, however, some earthquakes which caused considerable damage, while the greatest observed macroseismic intensity was VIII at the MM scale. These earthquakes were either intermediate in depth and originated from southern areas, or may have originated by an activation of a close source which might have been located in Taygetos or Parnonas, as the kind of damage and their extent indicate.

The epicenters of the earthquakes recorded in the study area by a local seismological network installed for ten weeks (August–October 1996), show a concentration along the western flanks of Parnonas (Figure 5(a)). These micro-earthquakes are mainly located at depths less than 20 Km and cannot be correlated with any microseismic activity originating from the Sparta fault (Figure 5(b)) Their origin should be related to active faults in the Parnonas area which, however, do not have surface indications.

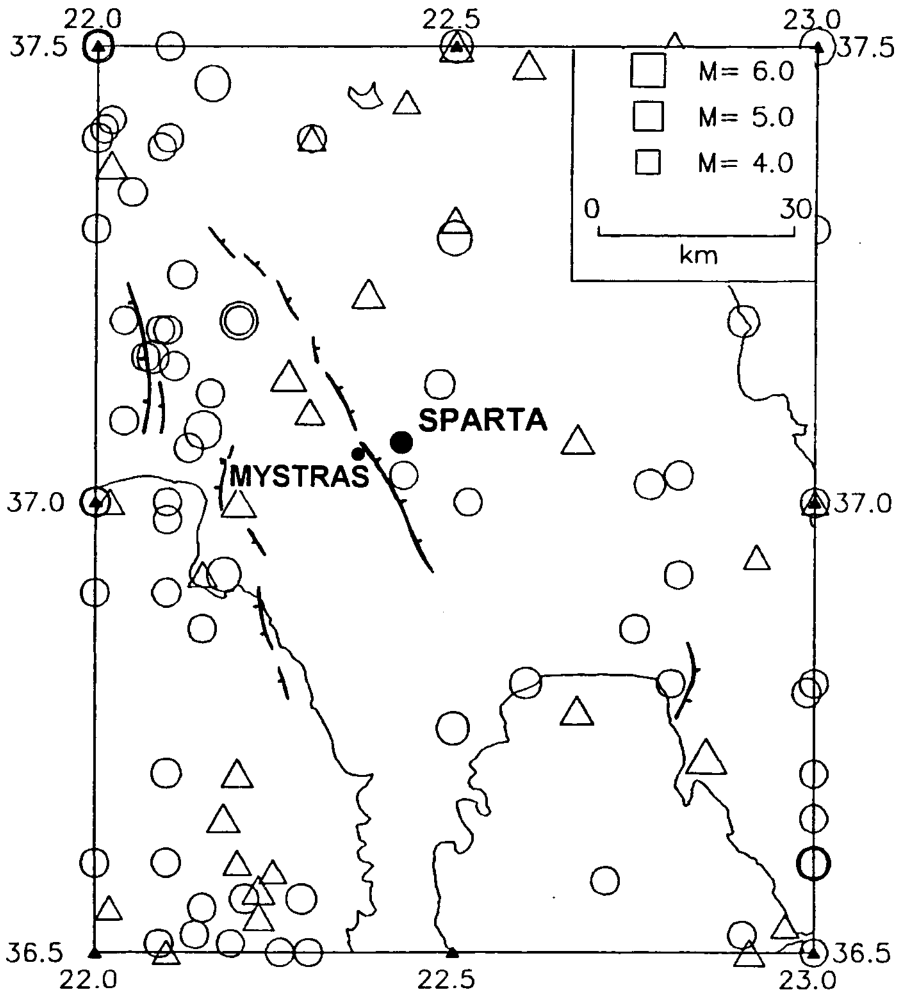

Figure 4. Spatial distribution of the earthquakes that have occurred in the present century in the broader area of Mystras–Sparta. Circles give the epicenters with focal depth less than 20 Km and triangles with focal depth greater than 20 Km.

All of the aforementioned suggest that the Sparta fault is under seismic quiescence, while the recurrence interval for strong earthquakes is greater than 2500 years. This behavior is very common among big active normal faults as exemplified by similar cases in Greece (Armijo *et al.*, 1992; Pavlides *et al.*, 1996). Nevertheless, this has to be regarded as a big active fault which could be reactivated at any time in the future.

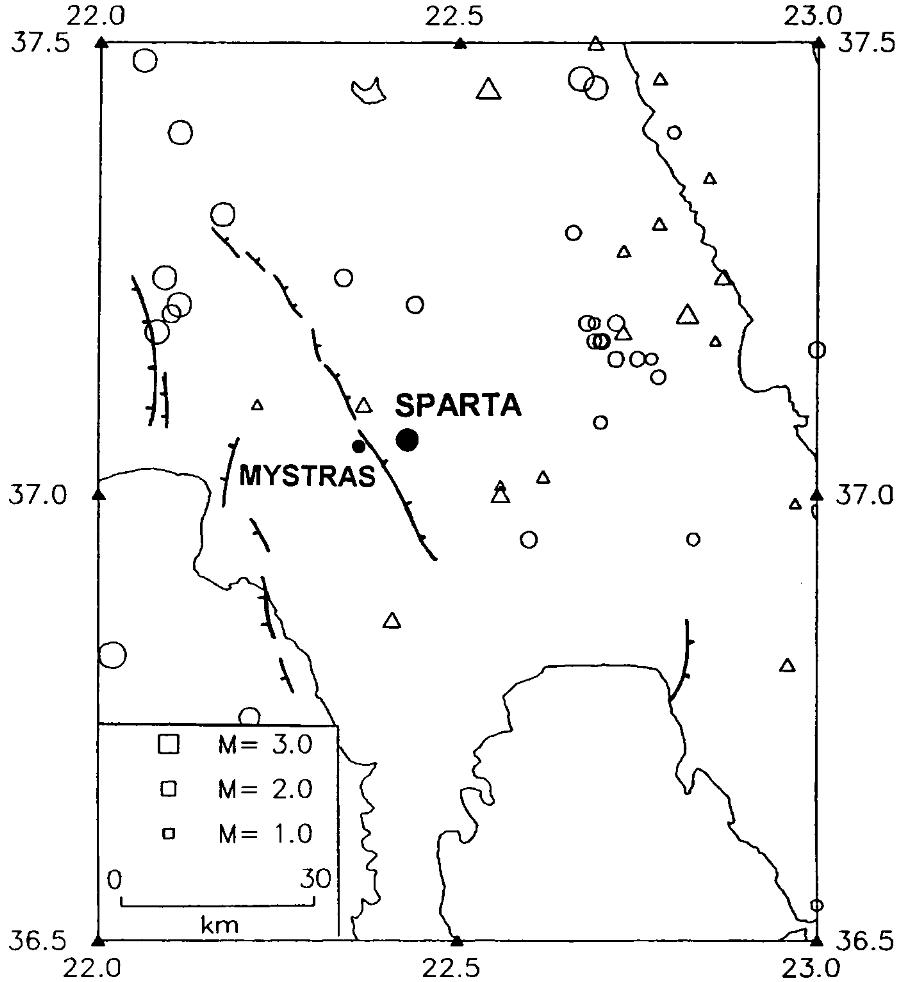

Figure 5a. Spatial distribution of the earthquakes that have been recorded by the local network in the broader area of Mystras–Sparta. The circles indicate the epicenters with focal depth less than 20 Km and the triangles indicate the epicenters with focal depth greater than 20 Km.

5. Seismic Hazard Assessment Studies

During the last 20 years a lot of research has been conducted in Greece, in order to assess its seismic hazard. This is based either on the theory of extremes or in the modeling of the earthquake epicenters surrounding a site that is as point, line or area sources. These studies covered the whole area of Greece and their results are presented in terms of earthquake magnitude, peak ground acceleration or velocity, or macroseismic intensity (Drakopoulos and Makropoulos, 1983; Hatzidimitriou, 1984; Makropoulos and Burton, 1985; Makropoulos *et al.*, 1988; Papaioannou, 1984; Papazachos *et al.*, 1993). Work has also been done on the

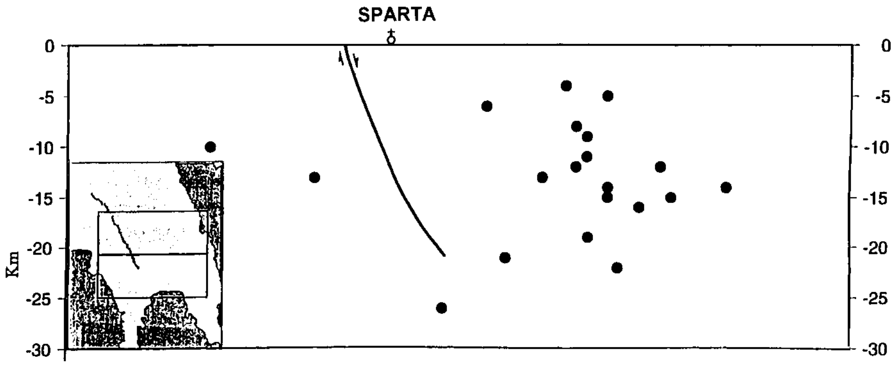

Figure 5b. Cross section perpendicular to the Sparta fault of the earthquakes that have been recorded by the local network.

simulation of strong ground motion (Stavrakakis, 1985; Margaris, 1994) and on the attenuation of spectral values of strong ground motion (Papoulia and Stavrakakis, 1990; Theodulidis, 1991).

The existing seismological data and historical information indicate that the study area is expected to give a relatively small number of strong earthquakes, and is characterized by an absence of epicenters of great earthquakes in short epicentral distances. Hatzidimitriou (1984), by using the well-known frequency–magnitude relation, estimated the values 0.95 and 3.99 for the parameters b and a respectively, the maximum observed earthquake magnitude is 6.8 while the annual rate of the earthquakes with $M > 5.0$ is 0.184. Moreover, he computed that the expected magnitudes, for the most probable annual magnitude, varies between 3.3 to 3.8, while those with return periods of 180 years range between 6.0 to 6.5.

Papanastassiou *et al.* (1996), in a hazard assessment study for central-south Peloponnesus by applying the modified Cornell method (Cornell 1968), computed, for the area of Mystras–Sparta, the values of 100, 150, 225 and 350 mgals for maximum expected peak ground acceleration with 90% probability not to be exceeded for return periods of 25, 50, 100 and 200 years, respectively.

Recently, the Greek Seismological Institutions, in a synthetic work, compiled a new seismic hazard map for Greece by using all the available seismic data and by applying different methods. Every Institute computed the expected strong ground motion at a mesh of grid points and the average values were finally obtained (Papazachos *et al.*, 1989). According to the New Seismic Code, which is now in operation, the Mystras–Sparta area belongs to a seismic zone for which the most probable maximum value of peak acceleration a_m is given by the formula:

$$\log a_m = 0.277 \log T_m + 1.579. \tag{1}$$

The final adopted values of a_m are about the 80% of those calculated by the above formula.

6. Estimation of the Ground Motion Based on Local Seismotectonic and Geologic Information and on Different Models of Rupture Propagation

Several studies (Espinoza, 1976; Idriss, 1978; Campell, 1981; Boatwright and Boore; 1982; Schwartz and Coppersmith; 1986; Abrahamson and Sommerville; 1996) have shown that besides the type of faulting (reverse or normal), the rupture propagation on the fault plane plays a predominant role on the ground motion. For this reason several attempts have been made to take its characteristics into consideration in computing the expected peak acceleration at a site. Midorikawa and Kobayashi (1978, 1980), and Kobayashi and Midorikawa (1982), proposed a method for estimating the response envelope of near-field ground motion with regard to local geological conditions, to fault characteristics and to rupture propagation. This method has already been used in different active zones in Greece (Stavrakakis *et al.*, 1991; Makaris *et al.*, 1992, 1993) and has also been applied in this study.

An outline of its concepts is as follows. The fault plane is divided into small subfaults. The envelope of the ground motion in a short period range (0.1–5 s) is represented by the superposition of the ground motion produced at every subfault. The characteristics of the seismic wave from each subfault, such as waveform envelope and response spectrum are determined from empirical relations and the peak acceleration values at the base rock are computed. Considering the general geological conditions of the investigated area, the corresponding values are obtained at the ground surface.

The velocity response spectrum $Sv(M, X, T)$ on free field bedrock is assumed to be a function of magnitude M and hypocentral distance X (km) in addition to period T (s) as follows:

$$\log Sv(M, S, T) = a(T)M - b(T) \log X - c(T). \tag{2}$$

The coefficients $a(T)$, $b(T)$ and $c(T)$ as well as the velocity spectra are after Kobayashi and Midorikawa (1982).

In order to compute the peak acceleration values the following assumptions have been made:

1. The envelope of the incident wave, is assumed to be of triangular form. Its duration is defined as the sum of the rupture duration and the time interval between the fastest and the slowest wave arrival at the site under investigation.

2. The envelope of the incident wave is regarded as the superposition of the pulses from the subfaults.

3. The envelope of an oscillator, whose damping is relatively large, is similar to that of the input motion.

4. The fault plane is divided into n elements (subfaults). By superposition of the finite elements the response envelope is obtained.

5. The peak acceleration can be estimated from the spectrum intensity by using the formula $A_{max} = 1.2 \times \text{MSI}$, where MSI is the modified spectrum intensity.

Moreover, the following relationship between intensity of response spectrum and peak acceleration has been found (Housner, 1965):

$$A_{\max} = 1.2 \times \int_{0.1}^{0.5} Sa(T)\,\mathrm{d}T. \tag{3}$$

Once the peak acceleration has been computed at the bedrock, the boundary whose shear wave velocity is approximately 3 km s^{-1}, the surface acceleration can be obtained by using the amplification factors, 5.5 for Quaternary, 3.5 for Neogene and 2.5 for Pre-Neogene (Kobayashi and Midorikawa, 1980).

The seismic and morphotectonic results suggest that the Sparta fault has to be considered as a big active fault which could be reactivated at any time in the future. Taking into account its seismotectonic characteristics (length and maximum scarp height) and comparing these with other faults of the area of Peloponnesus (Lyon-Caen *et al.*, 1988), it is concluded that this fault has the potential of producing strong earthquakes of magnitude of the order of 7.0. The ground accelerations which would be produced by a future activation of this fault were calculated for different magnitudes (6.0, 6.5 and 7.0) and taking into account the geometric parameters of the fault (length 20 km, focal depth 15 km, average direction N30°W and dip 40°E), the fracture pattern (normal fault with footwall located on the east side of the fault trace), and the properties of the propagation medium of the seismic ray. The accelerations were computed first at the base-rocks of the Mystras and Sparta, and then, by applying amplification factors at the surface. More precisely, for the Mystras area the factor of 2.5 is used for the scree-unconsolidated deposits, while for the Plio-Pleistocene sediments that underly the city of Sparta the factor of 3.5 is used. As the rupture propagation plays a predominant role on the ground motion, different scenarios of unilateral, bilateral and circular rupture were examined. The obtained results are given in Table I.

7. Conclusions

The obtained results have shown that the expected maximum values of ground acceleration at the basement of the two sites, Mystras and Sparta, are not the same. They strongly depend on the location of the site with respect to the rupture type and propagation. The highest values for the Mystras area (345 mgals) correspond to activation of the Sparta fault with a unilateral rupture along the strike starting from the southernmost point of the fault, while for Sparta city (421 mgals) for a unilateral rupture along the dip started from the lower point. For both sites maximum values are also estimated for a circular rupture starting from the depth, that is 348 mgals for Mystras and 326 mgals for Sparta.

These values are not very different compared with the maximum expected peak ground acceleration values estimated by the application of conventional seismic hazard methods (Papanastassiou *et al.*, 1998, New Seismic Code), although the latter correspond to hundreds of years return periods.

Table I. Calculated ground acceleration at Mystras and Sparta, produced by a future activation of the Sparta fault, for different magnitudes, rupture pattern and local ground conditions. The geometric parameters of the fault, the properties of the propagation medium of the seismic ray have been taken into account

Rupture mode	Magnitude	Calculated ground acceleration (mgals)			
		Mystras		Sparta	
		Basement	Surface	Basement	Surface
Unilateral rupture along the dip, higher to lower	6.0	41	102	57	199
	6.5	64	160	91	318
	7.0	105	262	152	532
Unilateral rupture along the dip, lower to higher	6.0	62	155	169	593
	6.5	96	241	258	904
	7.0	154	385	421	1473
Unilateral rupture along the strike, north to south	6.0	46	115	84	294
	6.5	70	175	133	465
	7.0	108	270	213	745
Unilateral rupture along the strike, south to north	6.0	141	253	102	357
	6.5	218	546	163	570
	7.0	345	863	266	931
Bilateral rupture along the dip	6.0	41	102	97	339
	6.5	65	163	153	535
	7.0	109	272	253	885
Bilateral rupture along the strike	6.0	78	196	62	217
	6.5	121	302	99	346
	7.0	196	489	165	577
Circular rupture, starts from the surface	6.0	37	92	58	203
	6.5	58	145	91	318
	7.0	92	231	146	511
Circular rupture, starts from the depth	6.0	145	363	124	434
	6.5	222	554	194	678
	7.0	348	871	326	1141

On the contrary, the estimated ground acceleration values for the surface, are quite high and especially for the case of Sparta, as these are amplified by a greater factor, corresponding to the overlay sediments. For the basement of the Mystras site, as it is composed by fragmented and low resistance limestones, which appear also on the surface, the ground acceleration which could be observed during a future earthquake might be greater than that calculated.

The obtained results for the retrospective application of this method in different ruptured active zones in Greece (Stavrakakis *et al.*, 1991; Makaris *et al.*, 1992; 1993), have shown that those of the unilateral rupture were in better agreement with the recorded ground accelerations. Accordingly, in the Mystras-Sparta case the obtained values of ground acceleration produced by unilateral rupture could be the most realistic for a future reactivation of the Sparta fault.

The application of this method is particularly useful in the determination of seismic hazard in areas of low seismicity for periods of hundreds or even thousands of years, having, however, the special characteristic of being in the neighborhood of an active seismic zone. The use of such methods in combination with detailed morphotectonic and seismologic studies, which could provide rates of the fault movements and average recurrence intervals, allows us to have a more complete knowledge of the seismic history of the area and a more realistic evaluation of its seismic hazard.

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