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Deterministic seismic hazard analysis for the city of Corinth-central Greece

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Abstract: *Deterministic seismic hazard analysis was performed for the city of Corinth. The city of Corinth has been chosen due to its seismic history. The city was destroyed in 1858 by an earthquake of magnitude* M_W*=6.5. The city was rebuilt a few kilometers away, only to be destroyed again during the devastating event of magnitude* M_W*=6.3 in 1928. We examined the seismic history of Corinth by taking into account all the earthquakes that occurred within distances of 30 and 50 km. The largest earthquake occurrence was within a radius of 30 km during the instrumental period (1981) and had a magnitude of* M_W*=6.7. For the radius of 50 km, two great events of magnitude* M_W*=7.0 occurred during the historical epoch (551 A.D. and 1402). In all calculations, the Peak Ground Acceleration (PGA) attenuation equation for shallow, crustal earthquakes in Greece has been applied. The attenuation equation incorporates information on soil conditions (rock, alluvium and intermediate). The examined city is a coastal site located mainly on alluvium type soil. The destructions of both, the old (1858) and the new (1928) city, happened because the epicenters of these earthquakes were very close, approximately 3 km and 5 km, respectively, from the centres of the cities. The corresponding PGA values generated by these earthquakes were respectively estimated as 0.32g and 0.31g. Maximum PGA values associated with "design earthquakes" were also evaluated by applying a deterministic procedure.*

Key words: *Maximum possible peak ground acceleration, design earthquakes, city of Corinth - Greece.*

INTRODUCTION

Greece is one of the most seismic active regions of the world (Tsapanos and Burton, 1991). The basic lithospheric process in the area is the subduction of the Africa plate under the Eurasia plate, south of Crete, and this makes Greece a natural seismological laboratory. The probabilistic seismic hazard analysis for Greece has, therefore, been widely studied using a number of different techniques and is expressed through different seismic quantities. Papulia and Slejko (1997) calculated seismic hazard for the towns of Argostoli, Lefkas, and Corfu in the Ionian islands (Western Greece), using local macroseismic intensities. Papaioannou and Papazachos (2000) assessed the time-independent seismic hazard for 144 broad sites (cities, towns, villages) of Greece in terms of expected macroseismic intensities. Tsapanos and Christova (2003) performed probabilistic seismic hazard analysis in terms of expected maximum values of Peak Ground Acceleration (PGA) in and around Crete. Seismic hazard parameters were estimated for three main cities of Crete (Tsapanos, 2003), while Mäntyniemi et al. (2004) applied a probabilistic procedure to estimate the seismic hazard for five metropolitan cities of Greece. An assessment of the expected ground motion in terms of PGA was derived by Makropoulos and Burton (1985). They presented hazard values which have a 70% probability of not being exceeded in a given time interval. PGA estimates of 0.12g, 0.14g and 0.16g were obtained for the respective time intervals of 25, 50 and 100 years in a radius of 100km around the city of Corinth.

Expected macroseismic intensities were estimated for 35 sites in Greece (including Corinth) using the classical method of Cornell and the mean-value technique (Papazachos et al., 1990). Our results are different since we focused on a very local cycle of 30 km around the city. Klügel et al. (2006) performed deterministic, scenario-based hazard analysis, which incorporates all the available information (seismotectonics, geology, etc).

The present study confines itself to the assessment of the level of seismic hazard for the city of Corinth, and is expressed in terms of the maximum possible PGA, produced by earthquakes in various distances, at the site of the new city. As stated above, the city was destroyed twice by large earthquakes. After the shock of 1858 the city was rebuilt a few kilometers away. The second large event of 1928 destroyed the new city but erroneously, it was rebuilt again at the same place. The present study focused mainly on the re-estimation of the seismic hazard, given the extensive development during the last twenty years observed in and around the new city of Corinth. Our results are based on the new Greek attenuation equation (Margaris et al., 2001), which were developed by utilizing the strong motion data recorded in Greece during the last 30 years.

Site-specific analyses of seismic hazard require knowledge of the attenuation of the chosen ground-motion parameter as a function of earthquake magnitude and distance. The attenuation equation for shallow earthquakes in Greece, derived by Margaris et al. (2001), is adopted for the purpose of our study. The effect of soil conditions (rock, intermediate and soft) is also taken into account. We employ the technique introduced by Kijko and Graham (1998, 1999), as well as by Kijko (2004). The technique makes provision for the earthquake catalogue to contain historical (incomplete) and recent (complete) data. The complete part of the catalogue can be divided into several sub-catalogues, each of which provide the complete set of events above a given threshold magnitude, occurring in a certain period of time. Uncertainty in earthquake magnitude may also be taken into account. Another advantage of the method adopted, is that it does not rely on the definition of seismic sources and/or seismic zones, which may involve subjective judgment.

GEOLOGICAL SETTING

The Gulf of Corinth corresponds to a 110 km long and 5-30 km wide graben, with a maximum depth of 880 m, trending WNW-ESE, and intersects the main trend of external Hellenides at almost right angles. Active deformation in the Gulf is recognised by uplifted shorelines, reversal of the drainage pattern, earthquake triggered landslides occurring both onshore and offshore, faulted colluvial wedges and historical and reported seismic activity data (Koukouvelas et al., 2005; Gallousi and Koukouvelas, 2007). Extensional deformation in the Gulf of Corinth initiated in Pliocene times (Ori, 1989; Doutsos and Piper, 1990; Roberts, 1996; Briole et al., 2000; Doutsos and Kokkalas, 2001), while the uplift of the southern inland part of the Corinth graben began in the early Pleistocene (Doutsos and Piper, 1990). This extension appears to be accommodated by both WNW- and ENE-trending normal faults dominating the western and the eastern part of the gulf respectively (Jackson et al., 1982; King et al., 1985; Ambraseys and Jackson, 1990; Doutsos and Piper, 1990; Roberts and Koukouvelas, 1996; Doutsos and Kokkalas, 2001). In general, the main active faults within the Gulf are 10-15 km long (Fig. 1), dipping either north or south at moderate angles (50º-60º). They also display segmentation along their length, with each individual fault segment extending less than 10 km long (Koukouvelas and Doutsos, 1996; Koukouvelas et al., 1999; Zygouri et al., 2008). These faults generate a spectacular relief in the south and well-defined but smoother fault scarps in the north affecting the basin architecture, the present – day bathymetry of the Gulf and the relatively frequent appearance of strong earthquakes (Doutsos and Piper, 1990; Collier et al., 1992; Dia et al., 1997). Especially, the eastern end of the Gulf of Corinth experienced by a number of major historical events. The most important are the events of 303BC, 551, 1402, 1858, 1928 and the seismic sequence of 1981 (Ambraseys and Jackson, 1990, 1997; Papazachos and Papazachou, 1997; Papadopoulos, 2000). Focal depths of these large earthquakes occurred near the base of the seismogenic layer at a depth of 10-15 km (Rigo et al., 1996). Based on palaeoseismological data for the faults named Kaparelli (Kokkalas et al., 2007), Skinos (Collier et al., 1998) and Kenchreai (Zygouri, 2009), the typical throw per event within the eastern part of the Gulf ranges from few centimeters to 1.0 m with a recurrence interval of up to 900 years (Chatzipetros et al., 2005). A north-south extension of the Corinth gulf, that resulted in 450-700 mm displacement (Ambraseys and Jackson, 1990), takes into account events with surface magnitude Ms>5.8 between 1890 and 1988. Similar results were estimated by Papazachos and Kiratzi (1992) for the same area. Based on an equation derived by Papazachos and Papazachou (1997), these displacements correspond to earthquake magnitudes between 6.5 to 7.0. Such shocks occurred in both short or longer distances from Corinth.

The simplest approach in trying to determine the correlation between significant seismic events, with active faults, is the estimation of their structural proximity. Although historical data may involve many uncertainties concerning their actual epicenter location, a great number of them assigns along well – known active fault arrays. In Figure 1, one can notice that the events of 303BC, 543, 580, 1402, 1742, 1753 and 1887 can be related to the faults lying on the north coast of Peloponnesus like Xylokastro and Corinthos faults. In addition, another cluster of events located near the city of Corinthos (as the 521, 1858, 1928 and 1930 events) is attributed to faults on the southeasternmost sector of the Gulf such as Kenchreai and Loutraki faults (Fig. 1). Moreover, the rupturing of the faults, dominating the northern side of the Gulf (as the Delfi fault, the Elikon fault and the Neochori fault), is possibly correlated with the strong events of 551, 1893 and 1914 (Fig. 1). Finally, the more recent and well-studied 1981 Alkyonides seismic sequence, involving three strong events, is associated with the surface faulting and vertical movements on two significant fault systems, namely Pissia – Skinos fault zone (PF and SKF in Fig. 1) and the Kaparelli fault (KF in Fig 1), (Morewood and Roberts, 2001; Kokkalas et al., 2007).

The event of 551 puts strong arguments among the seismologists if it was one isolated event or a seismic sequence. Sieberg (1932) considers the event of 551 as a seismic sequence which lasted from spring to summer. Papaioannou et al. (1994) agree with Sieberg and claims that it represents a seismic sequence that affected an area extending from the Maliakos Gulf in Central Greece to the Gulf of Corinth. However other authors (Evangelatou-Notara, 1995; Papazachos and Papazachou, 1997; Papadopoulos, 2000) disagree with this idea based on great distance between the Maliakos and the Gulf of Corinth as well as the dispersion of the damages. Therefore, they support the existence of a single event. Given that we do not have accurate information about this event, we adopted the magnitude, epicenter and origin time as provided by Papazachos and Papazachou (1997).

DATA USED

The seismic catalog of Greece contains events starting in 550 BC (Papazachos and Papazachou, 1997). Earthquakes were reported based on the level of shaking and the damage caused in populated areas. Hereafter we shall refer to the ancient Corinth as the old city (37.90^o N-22.88^o E) and to the new Corinth as the city of Corinth. A total of 12 large earthquakes with magnitude Mw>6.0 have been reported and recorded within the considered circle of radius 30 km around the city of Corinth. Another radius of 50 km is taken into account in order to check the occurrence of large earthquake in greater distances and the effect of them in the examined site. The check provided the existence of two great earthquakes in 551 A.D. and 1402 both with magnitude Mw=7.0 occurred in distances 50 and 48.7 (≈49) km from the city of Corinth. The total number of large earthquakes (magnitude Mw>6.0) observed with in the 50 km radius is 25 (13 more shocks were found between the circles of 30 and 50 km). The three events of February-March 1981 belong to the aftershock sequence of Alkyonides islands (Corinth gulf). The main shock was on 24 February 1981 and only this is taken into account for further processing. The two aftershocks (25 February 1981 and 4 March 1981) are listed in Table 1 just for illustration and this depends to their magnitude which exceeds 6.0. In Table 1 we have listed the 25 main large earthquakes (and the two aftershocks of 1981), their magnitudes and their distances from the city of Corinth (37.94^o N-22.93^o E). This radius is not arbitrarily chosen. It is based on a relationship given by Papazachos (1989) between the fault length and earthquake magnitude. The circle of a radius of 30 km therefore corresponds to a magnitude of 6.5, which is very close to the largest reported earthquake in the area (M=6.7-1981). According to the same authors an earthquake with magnitude M=7.0 corresponds to a fault length equal to 50 km. The magnitudes referred to, are in accord to those estimated from geological observations, reported to the geological setting of the present study.

Our earthquake data was mainly extracted from the data bank of the Geophysical Laboratory of the Aristotle University of Thessaloniki (Papazachos et al., 2000). The events up to 2007 were taken from the monthly bulletins of the same institute. The earthquake size is expressed in terms of moment magnitude (Papazachos et al., 1997). For additional information and especially for the historical events, we also considered the works of Papazachos and Papazachou (1997), Papadopoulos (2000) and Guidoboni et al. (1994). The data used were purged of foreshocks and aftershocks using the relationship derived by Papazachos and

Papazachou (1997), in which the duration of foreshocks and aftershocks depends on the magnitude of the main shock.

Completeness of the data is essential for such studies. Completeness of the data was assessed by dividing the time span of the catalogue into five sub-catalogues, and plotting the cumulative number of reported earthquakes above a threshold magnitude level with time. The determined time periods as well as the corresponding levels of completeness are illustrated in Table 2. Earthquakes occurred before 1910 are considered as historical events, given that the first Greek network installation was done in 1911. The errors on epicenters and magnitudes are less than 20 km and 0.2 magnitude units for the instrumental period, while the same errors for the historical period are less than 30 km (in epicenters) and in few extreme cases reach the 0.4 magnitude units (Papazachos and Papazachou, 1997).

Figure 2 shows the seismicity in the area of Corinth within the radius of 30 km (solid circle) and 50 km (dashed circle). The earthquakes with magnitude Mw>6.0 are depicted with stars. A first inspection of Figure 2, (for the 30 km radius) reveals that there are only 10 events of magnitudes greater or equal to 6.0. This is a result of a coincidence in the epicenters of the earthquakes of 74 and 1775. Similarly, the epicenters of the events of 543 and 580 coincide, as well. The earthquakes of 1858 and 1928 (years of destruction of the old and new city) are also pointed out. The old city is denoted by black rectangle, while the city of Corinth is denoted by a black triangle. The study is restricted to only shallow earthquakes (h<60 km), although there is knowledge of the occurrence of earthquakes of intermediate depth in the examined area. The number of these intermediate depth earthquakes is very limited (3 in the circle of 30 km and 6 in the circle of 50 km) and for this reason we do not considered them in the present study.

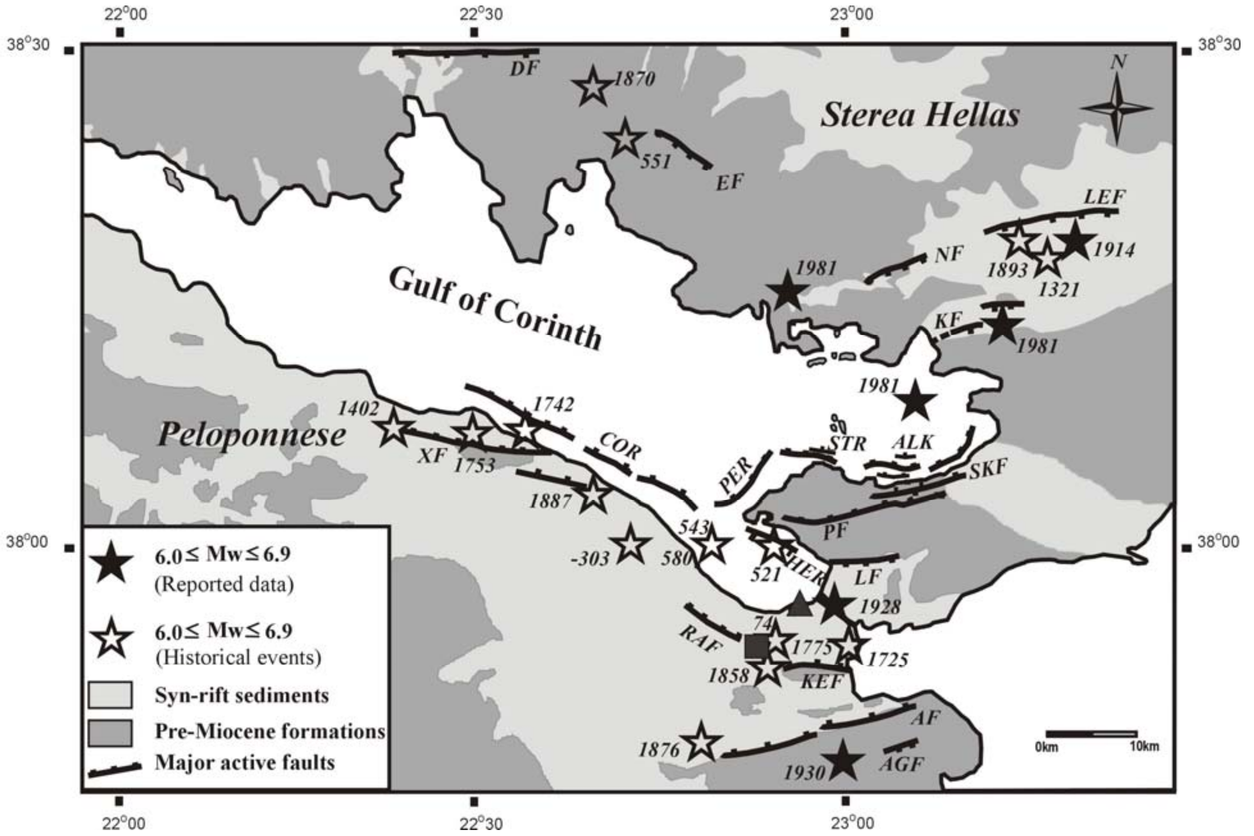

FIG. 1. Main active faults lying on the eastern side of the Gulf of Corinth and major earthquake events associated with them. The abbreviation meanings are DF: Delfi fault, EF: Elikon fault, NF: Neochori fault, LEF: Leontari fault KF: Kaparelli fault, ALK: Alkyonides fault, STR: Strava fault SKF: Skinos fault, PF: Pissia fault, PER: Perachora fault, HER: Heraio fault, LF: Loutraki fault, KEF: Kenchreai fault, AF: Athikia fault AGF: Agios Ioannis fault, RAF: Rachiani fault, COR: Corinthos fault, XF: Xylokastro fault.The location of the old city is marked with a black rectangle, and the new city of Corinth with a black triangle.

TABLE 1. The 25 main large earthquakes occurred within the circles with a 30 km (12 shocks-in bold) and a 50km (13 shocks) radius around the city of Corinth. The distance (DIST) from the city of Corinth is also provided in the last column. The minus symbol (-) means that the earthquake occurred during the B.C. period. Blank cells mean unavailable data.

YEAR	MONTH	DAY	TIME	LAT.	LONG.	MAGN.	DIST. (km)
-480				37.90	23.30	6.3	32.8
-388				37.60	22.80	6.2	39.2
-303				38.00	22.70	6.6	**21.5**
74	06	20		37.90	22.90	6.3	**6.0**
521				38.00	22.90	6.3	**7.5**
543				38.00	22.80	6.2	**13.4**
551				38.40	22.70	7.0	50.0
580				38.00	22.80	6.3	**13.4**
1321				38.30	23.30	6.3	49.6
1402	06			38.11	22.41	7.0	48.7
1421	12	10		37.50	22.90	6.5	48.2
1725				37.90	23.00	6.0	**7.5**
1742	10	22		38.10	22.60	6.7	33.9
1753	03	06		38.10	22.50	6.7	41.9
1775	04	16		37.90	22.90	6.3	**6.0**
1788	10	15		37.50	22.80	6.1	49.4
1858	02	21	09	37.87	22.88	6.5	**10.0**
1873	07	25		37.70	23.20	6.0	35.0
1876	06	26		37.80	22.80	6.1	**20.0**
1887	10	03	22:52:58	38.05	22.65	6.5	**27.4**
1893	05	23	22:02:00	38.31	23.25	6.3	49.7
1914	10	17	06:22:32	38.31	23.34	6.0	50.0
1928	04	22	20:13:44	37.94	22.97	6.3	**5.0**
1930	04	17	20:06:40	37.78	22.99	6.0	**18.3**
1981	02	24	20:53:37	38.07	23.00	6.7	**26.3**

TABLE 2. The time periods and the corresponding completeness thresholds of the magnitude for the five subperiods of the catalogue used.

Time peiods	Magnitude
1910-2007	$M \geq 5.3$
1943-2007	$M \geq 5.0$
1975-2007	$M \geq 4.7$
1982-2007	$M \geq 4.0$
1995-2007	$M \geq 3.0$

TABLE 3. The three parameters considered for area-specific processing. The maximum ever observed earthquake magnitudes within the circles of 30 and 50 km from Corinth are also listed.

Circle (in km)	30	50
M_{max} ± sd	6.71 ± 0.20	7.02 ± 0.31
λ ± sd (for $M \geq 3.0$)	15.54 ± 1.16	39.47 ± 1.92
b ± sd	0.96 ± 0.02	0.95 ± 0.03
Maximum observed M	6.7	7.0

METHODOLOGY

The concept of maximum magnitudes (possible, historical, etc) was defined by Reiter (1990). Based on this, a procedure called parametric-historic developed by Kijko and Graham (1998, 1999) and was applied in the present work to quantify the level of seismic hazard at the given site. From a computational point of view the applied procedure consists of the assessment of both area-specific and site-specific hazard parameters. Here our focus is on the second aspect. However, we first have to evaluate the area specific parameters which are: maximum possible magnitude M_{max}, the mean rate of seismic activity, λ, and the *b*-value of the Gutenberg - Richter frequency-magnitude relation for the areas of 30 and 50 km radius surrounding the site. The maximum regional earthquake magnitude M_{max} was estimated by applying the Bayesian extension of the Kijko-Sellevoll estimator, as described by Kijko (2004). These three parameters and their standard deviation (sd) for the circles of 30 and 50 km around the city of Corinth are listed in Table 3.

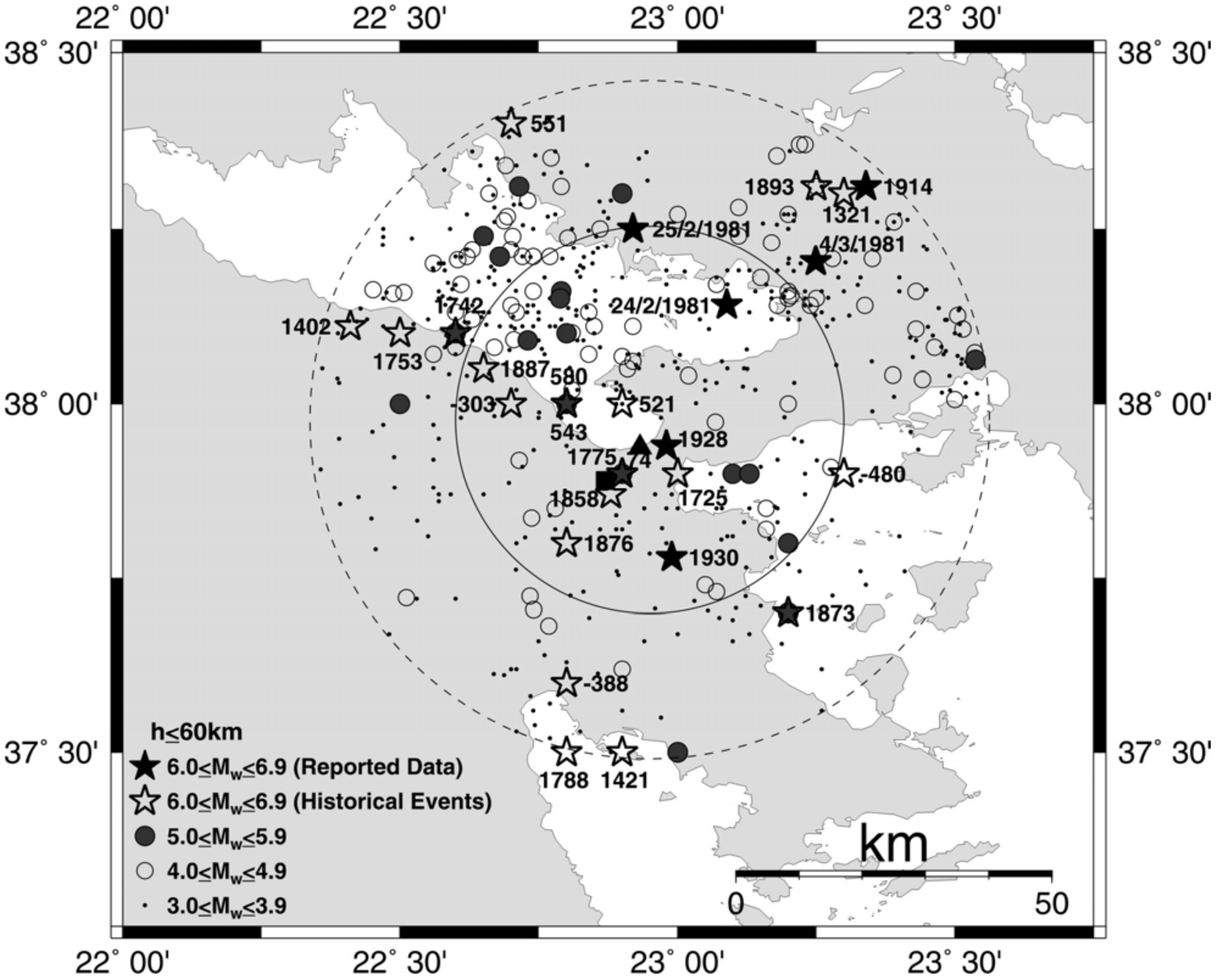

FIG. 2. The seismicity around the city of Corinth. The solid line circle illustrates the radius of 30 km, while dashed line represents the circle of 50 km. Stars denote events with magnitudes M_w>6.0 (black stars are the recorded data and the open stars are the historical events). The site of the old city is depicted with a black rectangle, while the present site of the city of Corinth is demonstrated with a black triangle. The three seismic events, shown with complete date (day, month and year), belong to the Alkyonides sequence of 1981.

The evaluation of the maximum regional magnitude $M_{\max}^{reg}$ is based on the condition that the largest observed magnitude $M_{\max}^{obs}$ is equal to the maximum expected magnitude $E(M_{\max}/T)$ in the span of the catalogue, and this condition provides a quite satisfactory estimate of $M_{\max}^{reg}$ (Kijko, 1988). If this equation is applied to the Gutenberg-Richter magnitude distribution, the following estimator of maximum regional magnitude $M_{\max}$ is obtained (Kijko and Graham, 1998):

$$M_{\max}^{reg} = M_{\max}^{obs} + \frac{E_1(TZ_2) - E_1(TZ_1)}{\beta \exp(-TZ_2)} + M_{\min}\exp(-\lambda \mathrm{T}) \qquad (1)$$

The quantities in equation (1) are computed as: $Z_1=\lambda A_1/(A_1-A_2)$, $Z_2=\lambda A_2/(A_1-A_2)$, $A_1=\exp(-\lambda M_{\min})$, $A_2=\exp(-\lambda M_{\max}^{obs})$ and $E_1(\cdot)$ denotes an exponential integral function (Abramowitz and Stegum, 1970):

$$E_1(Z) = \int_Z^{\infty} \exp(-\zeta)/\zeta d\zeta \qquad (2)$$

It is not difficult to show that the approximate variance of the maximum regional magnitude $M_{\max}^{reg}$ estimated according to equation (1) is equal to that derived by Kijko and Graham (1998):

$$Var(M_{\max}^{reg}) = \sigma_M^2 + \left[\frac{E_1(TZ_2) - E_1(TZ_1)}{\beta \exp(-TZ_2)} + M_{\min}\exp(-\lambda T)\right]^2 \qquad (3)$$

where we assumed that the observed (apparent) magnitude is distorted by an observational error, which is distributed normally with a know standard deviation σ_M, following the applied procedure of Tinti and Mulargia (1985a).

The site-specific computations require knowledge of the attenuation of the selected ground-motion parameter, *a*, as a function of earthquake magnitude and distance. In this work the attenuation equation of PGA for shallow, crustal earthquakes in Greece, derived by Margaris et al. (2001), was used:

$$\ln(a)=c_0+c_1\cdot M_w+c_2\cdot \ln(R^2+h_0^2)^{1/2}+c_3\cdot S\pm c_4 \qquad (4)$$

where, *a* is PGA, *R* is the epicentral distance (in km), h_0 = 7 km and the values of the coefficients are c_0 = 3.52, c_1 = 0.70, c_2 = -1.14 and c_3 = 0.12, while the standard deviation of ln(PGA) is given by c_4 = 0.70. S describes soil classification, taking on values 0, 1 or 2 corresponding to rock (hard), intermediate and alluvium (soft) conditions, respectively. The attenuation equation of equation (4) provides acceleration values in units of cm/sec^2.

The procedure based on the concept of the "design" earthquake was used to derive the maximum PGA at the examined site. The procedure can be seen as a variant of the technique known as "scenario" earthquakes (Ishikawa and Kameda, 1993). According to this procedure, a_{max} is the value of PGA computed from the attenuation relationship by assuming the occurrence of the strongest possible earthquake with magnitude $M_{\max}^{pos}$ at very short distance.

Tinti and Mulargia (1985a,b) introduced the concept of apparent earthquake magnitude which is defined as the "true" earthquake magnitude distorted by an error, which is assumed normally distributed with zero mean and standard deviation σ_M. A similar assumption is made regarding the error in the determination of epicentral distance R where the standard deviation of *R* is known and equal to σ_R. If the above assumptions are accepted, one can show that for an earthquake with an apparent magnitude *M*, located at a distance *R*, the value of ln(PGA) is approximately normally distributed with the mean given by the RHS of equation (4) and the standard deviation similar to the one derived by Kijko and Graham (1999):

$$\sigma_{TOTAL}=\sqrt{\sigma^2_{\ln(PGA)}+c_2^2\sigma_M^2+\sigma_R^2\left(\frac{R}{R^2+h_o^2}\right)^2} \qquad (5)$$

where, σ_{TOTAL} is the total standard deviation of ln(PGA), which includes $\sigma_{\ln(PGA)}$, the standard deviation of equation (4) as well as the standard deviation of earthquake magnitude determination σ_M and the standard deviation of epicentral distance σ_R.

For an earthquake of apparent magnitude *M* which is located at a distance *R* from a site, the probability that this earthquake will cause a PGA equal to or greater than *a* is given by:

$$\Pr\left[PGA\geq a\right]=1-\Phi\left(\frac{\ln(a)-\ln(\bar{a})}{\sigma_{TOTAL}}\right) \qquad (6)$$

where $\Phi(\cdot)$ is the normal probability integral (Abramowitz and Stegun, 1970):

$$\Phi(z)=(2\pi)^{-1/2}\int_{-\infty}^{z}\exp(-0.5t^2)dt \qquad (7)$$

and $\bar{a}$ is the median value of acceleration, with:

$$\bar{a}=a(0.5)=\exp\left[c_0+c_1M_w+c_2\ln\left(\sqrt{(R^2+h_0^{\,2})}\right)+c_3S\right] \qquad (8)$$

Following equation (6), the median value of PGA, $\bar{a}$, plus one standard deviation, i.e. *a*(0.84), takes the form:

$$a(0.84)=\bar{a}\cdot\exp\{\sigma_{TOTAL}\} \qquad (9)$$

The maximum credible PGA, $a_{\max}$, for the site of the city of Corinth was assessed by applying a deterministic procedure whereby $a_{\max}$ was calculated from the attenuation equation by assuming the occurrence of the maximum possible magnitude $M_{\max}^{pos}$ (Kijko, 2004) at a specified distance from the examined site.

RESULTS AND DISCUSSION

The maximum observed magnitude for the old city is M_w=6.6, having occurred in 303 B.C. (historical epoch) and was located about 22 km from the site. For the examined area of 30 km the estimated value of maximum possible earthquake magnitude $M_{\max}$ is 6.71±0.20, the estimated b-value of the Gutenberg-Richter relation is 0.96±0.02 and the mean seismic activity rate λ is 15.54±1.16 (for earthquakes with magnitude $M_w\geq3.0$). For the radius of 50 km we estimated $M_{\max}$=7.02±0.31, b=0.95±0.03 and λ=39.47±1.92. The results are checked with the transmission coefficient, which is an indicator of the correctness of the estimator (optimum value is 1.0). For the circle of 30 km this coefficient is 1.11, while for the circle of 50 km we found that the value of the same coefficient is 1.08. The errors of this coefficient in our estimations are very low namely 0.11 and 0.08, respectively. The significance of these results is also described by the earthquake hazard curves (Fig. 3). Furthermore the obtained results are very comparable with those estimated by Papaioannou and Papazachos (2000). This comparison is clearly shown to the b-values for the area (from 0.92 up to 0.96) evaluated by these authors.

The concept of the “design” earthquake can be used for the modelling of the “worst case scenario”, where we assume the occurrence of an earthquake with maximum possible earthquake magnitude $M_{\max}$ at a very small hypocentral distance, say 10 km, from the site. Clearly, the procedure provides a very conservative PGA value with a very small probability of occurrence. The approach should therefore provide more conservative results.

As it is shown in Table 1, the epicentral distances to all the largest earthquakes, from the city of Corinth, vary between 5 and 50 km. One can classify them into five groups, which are listed in Table 4. For each group we considered an error (σ_R) of ±5 km. The city of Corinth is located on soil considered to be soft. Table 4 shows results of calculation of $\alpha_{\max}(0.50)$, which is the maximum (median) value of PGA at the site of city of Corinth, and its upper 84% confidence limit $\alpha_{\max}(0.84)$. Calculations were performed for the five critical epicentral distances of $R_o=10\pm5$ km, $R_o=20\pm5$ km, $R_o=25\pm5$ km, $R_o=35\pm5$ km and $R_o=45\pm5$ km assuming an earthquake magnitude equal to $M_{\max}^{reg}$. Figures 4 and 5 show the probability that an earthquake of a certain magnitude at given distances will produce a PGA at a site exceeding a given value of acceleration.

It must be noted here that the newly approved seismic hazard code for territory of Greece predicts, corresponding to a 10% probability of exceedance in 50 years for the area of Corinth, a PGA value equal 0.24g. Our median value of PGA for distance of 10 km is equal 0.26g, which is almost the same as predicted by the new code.

The distance between the old and the new Corinth city is approximately 7 km. In our hazard estimates we concentrated mainly on the new city, but a short view on the destruction of the old city can be useful. It is believed that the destruction of the old city in 1858 took place because the earthquake occurred in a very close distance, approximately 3 km, from the city. For a hard rock site and earthquake of magnitude 6.5 at epicentral distance, R_o = 3 km, the predicted median value of PGA is 0.32g, while its 84th percentile, $\alpha_{\max}(0.84)$, is equal to 0.73g. Both values of PGA are very high and both were capable to destroy the city. It is assumed that the old city was built on hard rock, since it was located around its castle, away from the seashore.

The earthquake of 1928, which occurred about 5 km east of the city, completely ruined the city of Corinth. The predicted 84% value for PGA is equal to 0.62g, which is more than 2.5 times larger than the acceptable PGA value currently used in the seismic hazard code for the territory of Greece. Clearly a key role in this devastation was played by the soil type on which the city is located. Most of the Corinth city is located on relatively soft, alluvium type soil.

In this work, we made an assumption that future strong earthquakes may have the same magnitudes and will occur at the same epicentral distance as in the past. Our objective was to ascertain if the predicted PGA from such earthquakes would exceed the accepted PGA value of 0.24g as given by the Greek seismic hazard code. The results of such “scenario” earthquakes are shown in Table 5. Based on such predicted median values of $\alpha_{\max}$, we come to conclusion that only five of such earthquakes would be dangerous for the current city of Corinth. These were the earthquakes of 74, 521, 1775, 1858 and 1928 A.D..

Deterministic seismic hazard assessment for the broader area of Greece was carried out by Morrato et al (2007). Though their study was not focused on Corinth area, high hazard values resulted for this specific region.

Papazachos and Papazachou (1997) suggested that earthquakes in Greece generally cause damages when the PGA exceeds the value of approximately 0.09g. Table 5 reveals that the PGA values produced by 12 of the 25 large earthquakes, occurred in the investigated area, are greater than or equal to 0.09g. Descriptions about these disastrous shocks can be found in historical chronicles, as well as in the modern literature (for references see Table 5).

TABLE 4. Median α_{max} (0.50) and its upper 84% confidence limit, α_{max}(0.84) (in units of g) at the site of the city of Corinth for critical epicentral distances (R_o) of 10±5 km, 20±5 km, 25±5 km, 35±5 km and 45±5 km, as well as the maximum possible magnitude m_{max} as obtained by the application of the K-S-B estimator (Kijko, 2004).

R_o (in km)	**a_{max} (0.50)**	**a_{max} (0.84)**	**m_{max}±s.d.**
10 ± 5	0.28	0.61	6.71 ± 0.20
20 ± 5	0.15	031	6.71 ± 0.20
25 ± 5	0.11	0.24	6.71 ± 0.20
35 ± 5	0.10	0.21	7.02 ± 0.31
45 ± 5	0.07	0.16	7.02 ± 0.31

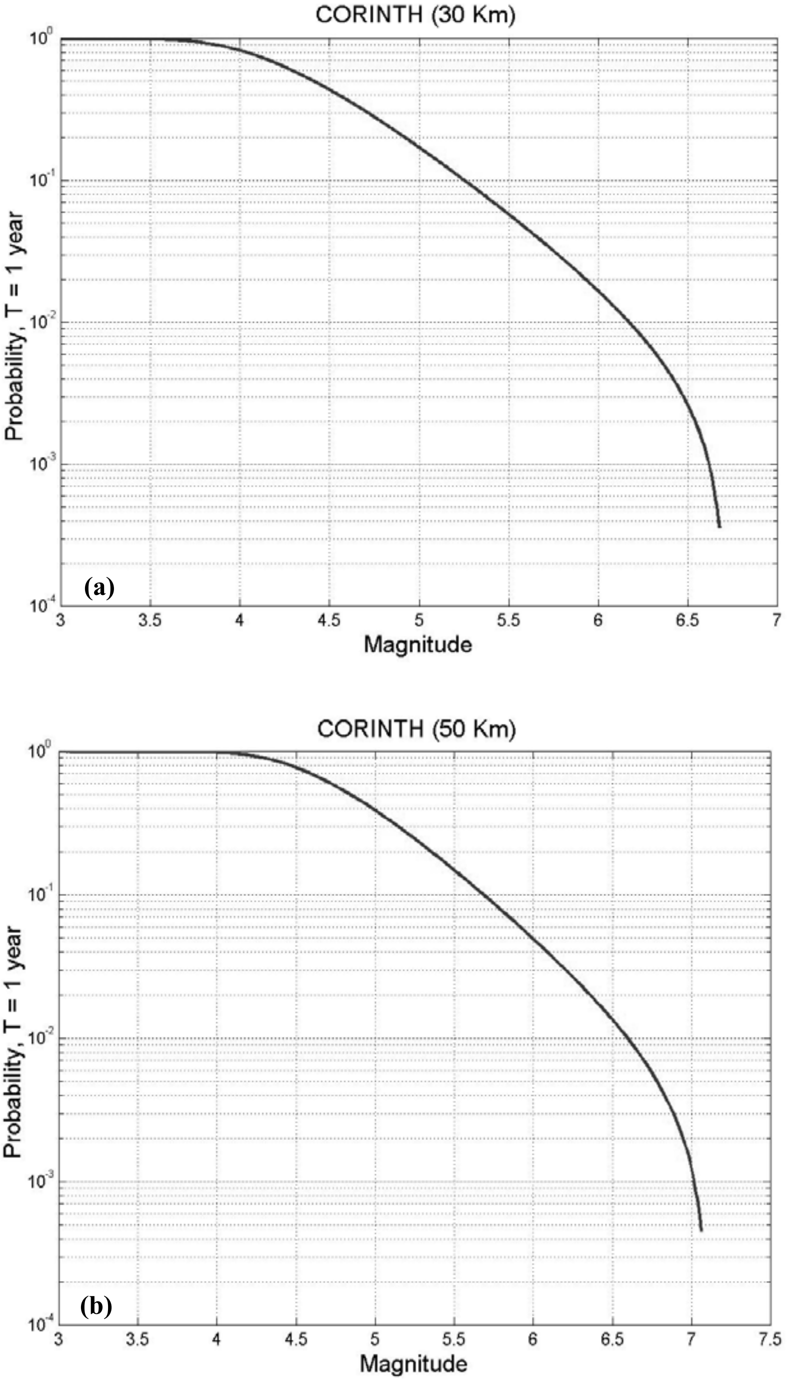

FIG. 3. Earthquake hazard curves expressed as a probability that a given magnitude will be exceeded during one year for: a) the circle of 30 km and b) for the circle of 50 km

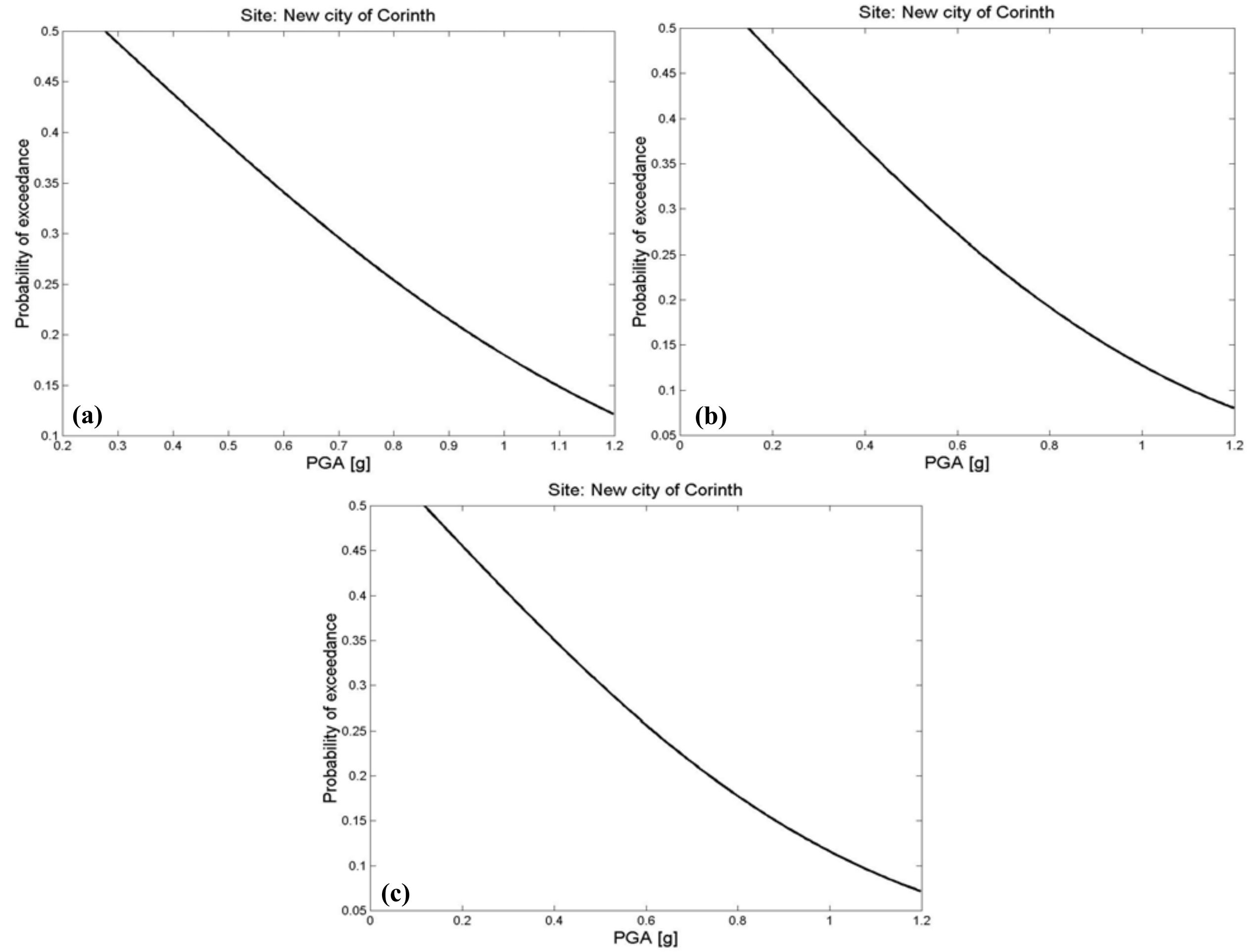

FIG. 4. The probability that an earthquake of magnitude m_{max}=6.71±0.20, will produce a PGA exceeding a given value at the city of Corinth, at a distance of: a) 10±5 km, b) 20+5 km and c) 25±5 km.

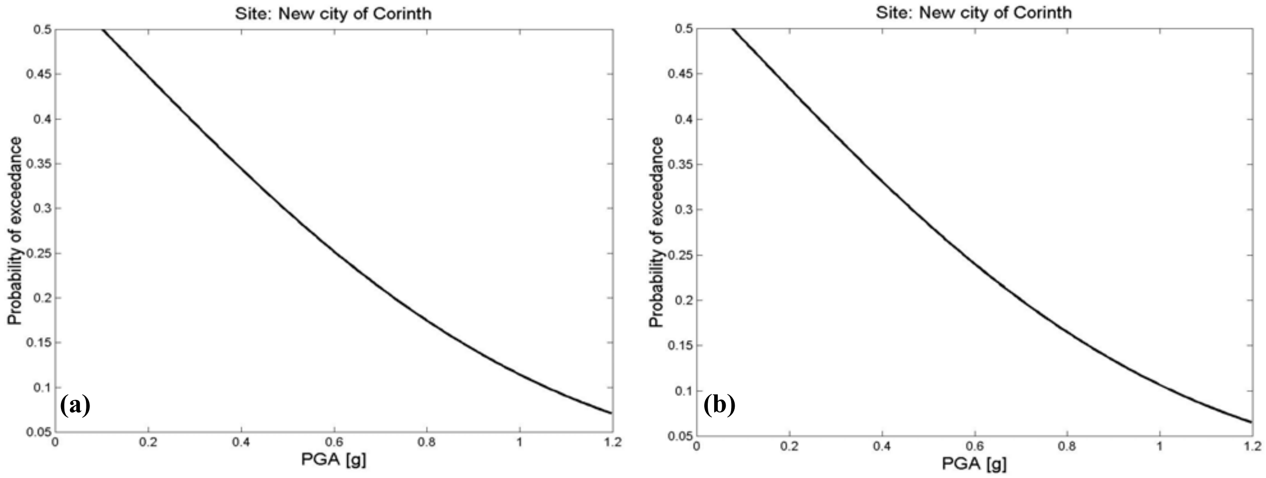

FIG. 5. The probability that an earthquake of magnitude m_{max}=7.02±0.31, will produce a PGA exceeding a given value at the city of Corinth, at a distance of: a) 35±5 km and b) 45+5 km.

TABLE 5. "Design" peak ground acceleration (PGA) values for the city of Corinth (new city), taking into consideration that the earthquakes that occurred in the past will strike again at the same epicenters. The five PGA values which exceed 0.24g, the maximum value of PGA acceptable by the Greek seismic hazard code, are marked in bold. The two aftershocks of 1981 are excluded from the present Table.

YEAR	a_{max} (0.50)	a_{max} (0.84)	Reference
-480	0.07	0.14	
-388	0.05	0.10	
-303	0.13	0.26	Bousquet et Pechoux (1978)
74	**0.29**	0.58	Georgiades (1904)
521	**0.25**	0.51	Sathas (1867)
543	0.15	0.31	Guidoboni et al. (1994)
551	0.07	0.13	
580	0.16	0.33	Evagelatou-Notara (1995)
1321	0.04	0.08	
1402	0.07	0.14	
1421	0.05	0.10	
1725	0.21	0.41	Ambraseys and Jackson (1990)
1742	0.08	0.17	
1753	0.07	0.13	
1775	**0.29**	0.58	Papadopoulos (2000)
1788	0.04	0.07	
1858	**0.25**	0.48	Koustas (1858)
1873	0.05	0.11	
1876	0.10	0.19	Schmidt (1879)
1887	0.09	0.18	
1893	0.04	0.08	
1914	0.03	0.07	
1928	**0.31**	0.62	Montandon (1953)
1930	0.10	0.20	Critikos (1932)
1981	0.11	0.23	Papazachos and Papazachou (1997)

CONCLUSIONS

The seismic hazard for the city of Corinth has been calculated. Areas of radii 30 and 50 km around the city were considered. During a period of 2300 years (time period covered by the Greek catalog of earthquakes) the area experienced 25 large ($M_w \geq 6.0$) main earthquakes, as well as 2 aftershocks of the same magnitude interval. The maximum possible earthquake magnitudes for the corresponding radii estimated as $M_w = 6.71 \pm 0.20$ and 7.02 ± 0.31. These estimates are very compatible to the results obtained by the geological observations. The maximum possible values of PGA at the examined site were estimated. In all the calculations the effect of soil conditions (city is situated on alluvium) was taken into account. Based on our assessments of PGA from the past 25 earthquakes listed on the Table 5, we conclude that during a period of 2300 years, the estimated median value of PGA, $a_{max}(0.50)$, exceeded 0.09 g twelve times.

Some elements of deterministic seismic hazard are also discussed. Assuming re-activations of the past 25 earthquakes with $M_w \geq 6.0$, we show that five of them, (occurred at 74, 521, 1775, 1858 and 1928 A.D.), can cause heavy damages to the city. The estimated value of PGA produced by these five events exceeds the Greek seismic code accepted value of PGA for the city of Corinth. Also from Table 1 we can see that 6 of the examined events occurred in very short distances ($\leq$ 10 km) from the studied site. The magnitudes of these shocks ranged between 6.0-6.5. These are mainly the real danger for the city of Corinth.

Very recently, Tselentis and his colleagues (2010a, b and c) estimated the seismic hazard of Greece using a number of various hazard parameters. In Tselentis and Danciu (2010a) the PGA values that were assessed, indicated that the obtained results are comparable with the ones of this study, leading to the conclusion that Corinth is under danger during the next occurrence of a large earthquake.

Corinth has had a very bad experience of earthquakes, given that the city was totally destroyed during the 1928 event. Since the city was rebuilt in the same place, it is exposed to significant risk, as demonstrated above. The results have been implemented to assess the seismic hazard and to offer an assist to governmental services (civil protection), civil engineers and planners to mitigate adverse social and economic effects of an earthquake and may be used in the process of designing important facilities such as hospitals, plants, etc. in and around the city of Corinth.

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REFERENCES

Abramowitz, M. and Stegun, I.A., 1970. Handbook of Mathematical Functions. 9th Edn. Dover Publications, New York, 1044pp.

Ambraseys, N.N, and Jackson, J.A., 1990. Seismicity and associated strain of Central Greece between 1890 and 1988. Geophys. J. Int., 101, 663-708.

Ambraseys, N.N. and Jackson J., 1997. Seismicity and strain in the Gulf of Corinth (Greece) since 1694. J. Earthquake. Eng. 1, 433-474.

Bousquet, B. et Pechoux, P., 1978. Recherches bibliographic sur la seismicite hstorique. Rapport Final D' Activite Scientifique De L' Equipe Du Laboratoire De Geologie Dynamique De L' Universite Paris Sud Le Resultat Des Edudes Neotectonique en Greece, 3, 47-65, 4, 93-126.

Briole, P., Rigo, A., Lyon-Caen, H., Ruegg, J., Papazissi, K., Mistakaki, C., Balodimou, A., Veis, G., Hatzfeld, D. and Deschamps, A., 2000. Active deformation of the gulf of Korinthos, Greece: results from repeated GPS surveys between 1990 and 1995. JGR 105, 25605-25625.

Chatzipetros, A., Kokkalas, S., Pavlides, S. and Koukouvelas, I., 2005. Palaeoseismic data and their implication for active deformation in Greece. J. Geodyn. 40, 170-188.

Collier, R.E.L., Leeder, M.R., Rowe, R.J. and Atkinson, T.C., 1992. Rates of tectonic uplift in the Megara basins, central Greece. Tectonics 11, 1159-1167.

Collier, R.E.L., Pantosti, D., D'Addezio, G., De Martini, P.M., Masana, E. and Sakellariou, D., 1998. Paleoseismicity of the 1981 Corinth earthquake fault: seismic contribution to extensional strain in central Greece and implications for seismic hazard. J. Geophys. Res. 103, 30001–30019.

Critikos, N.A., 1932. Le trempblement de terre du 7 April 1930 dans le golf Saronique. Ann. De l'Observ. Nat. d' Athens, 12, 233-237.

Dia, A.N., Cohen, A.S., O'nions, R.K. and Jackson, J.A., 1997. Rates of uplift investigated through 230Th dating in the Gulf of Corinth (Greece). Chemical Geology 138, 171-184.

Doutsos, T., and Piper, D.J.W., 1990. Listric faulting, sedimentation and morphological evolution of the quaternary eastern Corinth rift, Greece: first stages of continental rifting. Bull. Geol. Soc. Am. 102, 812-829.

Doutsos, T. and Kokkalas, S., 2001. Stress and deformation patterns in the Aegean region. J. Struct. Geol. 23, 455-472.

Evangelatou – Notara, F., 1995. And many of Peloponnese...became a prey of the earthquake. Proceed. of the 3rd Int. Meeting of Peloponnese Studies. Kalamata 8-15 September, 427-448.

Gallousi, C. and Koukouvelas, I.K., 2007. Quantifying geomorphic evolution of earthquake – triggered landslides and their relation to active normal faults. An example from the Gulf of Corinth, Greece. Tectonophysics 440, 85-104.

Georgiades, S.A., 1904. About earthquakes and antiseismic constructions. Publ. S. Koukoulinou, Athens, 306pp (in Greek).

Guidoboni, E., Comastri, A. and Traina, G., 1994. Catalogue of ancient earthquakes in the Mediterranean area up to the 10th century. SGA Storia Geofisica Ambiente, Bologna, 504 pp.

Jackson, J.A., Gagnepain, J., Houseman, G., King, G.C.P., Papadimitriou, P., Soufleris, C. and Vireux, J., 1982. Seismicity, normal faulting, and the geomorphological development of the Gulf of Corinth (Greece): the Corinth earthquakes of February and March 1981. Earth Plan. Sci. Lett. 57, 377-397.

Ishikawa, Y. and Kameda, H., 1993. Scenario-earthquakes vs. probabilistic seismic hazard. Proc. Int. Conf. on Structural Safety and Reliability, Innsbruck.

Kijko, A., 1988. Maximum likelihood estimation of Gutenberg-Richter b parameter for uncertain magnitudes values. Pageoph, 127, 573-579.

Kijko, A. 2004. Estimation of the maximum earthquake magnitude m_{max}. Pure Appl. Geophys, 161, 1-27.

Kijko, A. and Graham, G., 1998. Parametric-historic procedure for probabilistic seismic hazard analysis. Part I: Estimation of maximum regional magnitude m_{max}. Pageoph, 152, 413-442.

Kijko, A. and Graham, G., 1999. "Parametric-historic" procedure for probabilistic seismic hazard analysis. Part II: Assessment of seismic hazard at specified site. Pageoph, 154, 1-22.

King, G.C.P., Ouyang, Z.X., Papadimitriou, P., Deschamps, A., Gagnepain, L., Houseman, G., Jackson, J.A., Soufleris, C. and Virieux, J., 1985. The evolution of the Gulf of Corinth (Greece): an aftershock study of the 1981 earthquakes. Geophys. J.R. Astron. Soc. 80, 677-693.

Klügel, J. U., Mualchin, L and Panza, G.F., 2006. A scenario-based procedure for seismic risk analysis. Engin. Geol., 88, 1-22.

Kokkalas, S., Pavlides, S., Koukouvelas, I., Ganas A., Stamatopoulos L., 2007. Paleoseismicity of the Kaparelli fault (eastern Corinth Gulf): evidence for earthquake recurrence and fault behaviour. Boll. Soc. Geol. It. (Ital. J. Geosci.) 126, 387-395.

Koukouvelas, I.K. and Doutsos, T., 1996. Implications of structural segmentation during earthquakes. The 1995 Egio earthquake, Gulf of Corinth, Greece. J. Struct. Geol., 18, 1381-1388.

Koukouvelas, I.K., Asimakopoulos, M. and Doutsos, T., 1999. Fractal characteristics of active normal faults: an example of the eastern Gulf of Corinth, Greece. Tectonophysics, 308, 263-274.

Koukouvelas, I.K., Katsonopoulou, D., Soter, S. and Xypolias, P., 2005. Slip rates on the Helike Fault, Gulf of Corinth, Greece: new evidence from geoarchaeology. Terra Nova, 17, 158-164.

Koustas, G., 1858. Earthquake of Corinth. Pandora, 15 Ayg. 1858, 8, 225-229 (in Greek).

Makropoulos, K.C., and Burton, P.W., 1985. Seismic hazard in Greece. II. Ground acceleration. Tectonophysics, 117, 259-294.

Mantyniemi, P., Tsapanos, T.M. and Kijko, A., 2004. An estimate of probabilistic seismic hazard for five cities in Greece by usung the parametric-historic procedure. Engin. Geology, 72, 217-231.

Margaris, V., Papazachos, C.B., Papaioannou, Ch. A., Theodoulidis, N., Kalogeras, I. and Skarlatoudis, A., 2001. Empirical attenuation relations for the strong ground motion parameters of shallow earthquakes in Greece. Proc. 2nd Congr. Engineering Seismology and Earthquake Engineering, 28-30 Nov. 2001, Thessaloniki, Greece.

Montandon, F., 1953. Les tremblements de terre destructure en Europe. Catalogue par territoires seismiques de l'an 1000 a 1940. Geneva, 195pp.

Morrato, L., Orlrcka-Sikora, G., Costa, P., Suhadolc, Ch., Papaioannou, Ch. and Papazachos, C.B., 2007. A deterministic seismic hazard analysis for shallow earthquakes in Greece. Tectonophysics, 442(1-4), 66-82.

Morewood, N.C. and Roberts, G.P., 2001. Comparison of surface slip and focal mechanism slip data along normal faults: an example from the eastern Gulf of Corinth, Greece. J. Struct. Geol., 23, 473-487.

Ori, G., 1989. Geologic history of the extensional basin of the Gulf of Corinth (?Miocene – Pleistocene), Greece. Geology, 17, 701-707.

Papadopoulos, G.A., 2000. Historical earthquakes and tsunamis in the Corinth rift, central Greece. National Observatory of Athens, Institute of Geodynamics, public. No 12, 128pp.

Papaioannou, Ch.A. and Papazachos, B.C., 2000. Time-independent and time-dependent seismic hazard in Greece based on seismogenic sources. Bull. Seism. Soc. Am., 90, 22-33.

Papaioannou, Ch., Kiratzi, A., Papazchos, B. and Theodoulidis, N., 1994. Scaling of normal faulting earthquake response spectra in Greece. Bull. Geol. Soc. of Greece, XXX/5, 197-204.

Papazachos, B.C., 1989. Measures of earthquake size in Greece and surrounding areas. Proceed. of the 1st Hell. Geoph. Congress, Athens 19-21 April 1989, 438-447.

Papazachos, B.C. and Papazachou, C.B., 1989. The earthquakes of Greece. Ziti publications, Thessaloniki, 356pp (in Greek).

Papazachos, B.C., 1996. Large seismic faults in the Hellenic arc. Annali di Geofisica, 39, 891-903.

Papazachos, B. and Papazachou, C., 1997. The Earthquakes of Greece. Ziti Editions, Thessaloniki, 304 pp.

Papazachos, B.C., Papaioannou, Ch.A., Papastamatiou, D.J., Margaris, B.N. and Theodulidis, N.P., 1990. On the reliability of different methods of seismic hazard assessment in Greece. Nat. Hazards, 3, 141-151.

Papazachos, B.C., Kiratzi, A.A. and Karakostas, B.G., 1997. Toward a homogeneous moment-magnitude determination for earthquakes in Greece and the surrounding area. Bull. Seismol. Soc. Am., 87, 474-483.

Papazachos, B.C., Comninakis, P.E., Karakaisis, G. F. Karakostas, B. G., Papaioannou, Ch.A., Papazachos, C.B. and Scordilis, E.M., 2000. A catalogue of earthquakes in Greece and surrounding area for the period 550 B.C.-1999. Publ. Geophys. Laboratory, Univ. Thessaloniki.

Papazachos, C.B. and Kiratzi, A.A., 1992. A formulation for reliable estimation of active crustal deformation and an application to central Greece. Geophys. J. Int., 111, 424-432.

Papoulia, J.E. and Slejko, D., 1997. Seismic hazard assessment in the Ionian islands based on observed microseismic intensities. Nat. Hazards, 14, 179-187.

Reiter, L., 1990. Earthquake Hazard Analysis. Columbia University Press, New York 245pp.

Rigo, A., Lyon –Caen, H., Armijo, R., Deschamps, A., Hatzfeld, D., Makropoulos, K., Papadimitriou, P. and Kassaras, I., 1996. A microseismic study in the western part of the Gulf of Corinth (Greece): implications for large scale normal faulting mechanisms. Geoph. J. Int. 126, 663-688.

Roberts, G.P., 1996. Non – characteristic normal faulting surface ruptures from the gulf of Corinth Greece. J. Geophys. Res., 101, 255-267.

Roberts, G. P.and Koukouvelas, I. K., 1996. Structural and seismological segmentation of the Gulf of Corinth fault system: implication for models of fault growth. Annali di Geophysica 39, 619-646.

Sathas, K,N,, 1867. Medieval Seismologion of Greece and mainly of Cephalonia and Leukada. Can. 213-248 (in Greek).

Sieberg, A., 1932. Erdbebengeographie. Berlin, 687-1005.

Skourlis, K., Doutsos, T., 2003. The Pindos fold-and-thrust belt (Greece): inversion Kinematics of a passive continental margin. Int. J. Earth Sci., 92, 891-903.

Schmidt, J., 1879. Monographien von Grient Erdbeben 1837-1873, Alwin Georgi, Leipzig, 34-136.

Tinti, S. and Mulargia, F., 1985a. Effects of magnitude uncertainties in the Gutenberg- Richter frequency-magnitude law. Bull. Seismol. Soc. Am., 75, 1681-1697.

Tinti, S. and Mulargia, F., 1985b. Application of the extreme value approaches to the apparent magnitude distribution of the earthquakes. Pageoph, 123, 199-220.

Tsapanos, T. M., 2003. A seismic hazard scenario for the main cities of Crete island Greece. Geophys. J. Int., 153, 403-408.

Tsapanos, T.M. and Burton, P.W., 1991. Seismic hazard evaluation for specific seismic regions of the world. Tectonophysics, 194, 153-169.

Tsapanos, T.M. and Christova, C.V., 2003. Earthquake hazard parameters in Crete island and its surrounding area inferred from Bayes statistics: An integration of morphology of the seismically active structures and seismological data. Pageoph, 160, 1517-1536.

Tselentis, G-A. and Danciu, L., 2010a. Probabilistic seismic hazard assesement in Greece – Part 1: Enginnering ground motion parameters. NHESS, 10, 25-39.

Tselentis, G-A., Danciu, L. and Sokos, E., 2010b. Probabilistic seismic hazard assesement in Greece – Part 2: Acceleration response spectra and elastic input energy spectra. NHESS, 10, 41-49.

Tselentis, G-A. and Danciu, L., 2010c. Probabilistic seismic hazard assesement in Greece – Part 3: Deaggregation. NHESS, 10, 51-59.

Zygouri, V., 2009. Fault Interaction and seismic hazard assessment in the eastern part of the gulf of Corinth. PhD thesis, University of Patras, 1-272.

Zygouri, V., Verroios, S., Kokkalas, S., Xypolias, P. and Koukouvelas, I.K., 2008. Scaling properties within the Gulf of Corinth, Greece; comparison between offshore and onshore active faults. Tectonophysics, 453, 193-210.