A METHODOLOGY FOR RELIABLE SEISMIC HAZARD ASSESSMENT IN THE SOUTH BALKAN AREA

by

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Abstract

A methodology is suggested by which time independent and time dependent seismic hazard can be assessed at any site in the south Balkan area by taking into consideration several factors. These factors include seismicity parameters of the seismogenic sources where strong earthquake generation can affect the site, anisotropic radiation of seismic energy at the sources, attenuation of strong seismic motion along the wave path, site effect of broad sites (areas around city, town, village) and differences in the national practices for estimation of macroseismic intensity. The methodology includes also a validation test for the results by the use of macroseismic observations. It is further suggested that the identification of preshock (critical) regions in the crust of this area gives new possibilities for time dependent hazard. It is shown that these critical regions can be considered as circular, in a first approximation, and the logarithm of their radii is a linear function of the moment magnitude of the expected mainshock.

1. INTRODUCTION

Many papers have been published up to now on the seismic hazard assessment in the south Balkan area (Algermissen et al., 1976; Makropoulos and Burton, 1985; Papaioannou, 1986; Stavrakakis and Papoulia, 1990; Papazachos et al., 1990 among many others). Most of these works are based on the separation of the area in seismogenic sources, on the use of attenuation relations for the estimation of seismic hazard at a site and on application of methods suggested by Cornell (1968) and McGuire (1976). These methods, however, do not take into consideration all factors that affect seismic hazard. Some attempts have been made recently to investigate the effects of several factors on seismic hazard (Papazachos and Papaioannou, 1997, 1998) and to assess seismic hazard in this area by taking into consideration these factors (Papaioannou and Papazachos, 1999).

The purpose of the present paper is to present a realistic methodology for assessing time independent and time dependent hazard in the south Balkan area by taking into consideration all the basic properties of the seismogenic source, of the wave path and of the site which affect strong seismic motion. The possibility for the improvement of the methodology for time dependent hazard in the future is also examined by presenting some new results concerning critical preshock regions of the study area.

2. SEISMOGENIC SOURCES

Seismogenic sources are considered as that part of the lithosphere, which are relatively homogenous in respect to their seismotectonic properties. That is, seismicity is about uniform and the faults of the source are of the same type (thrust, normal, strike-slip) and of similar orientation (strike, dip, rake). A seismogenic source usually includes a main fault and other several faults. For seismic hazard assessment, it is necessary to define the boundaries of each seismogenic source, to calculate the relevant seismicity parameters and to determine the azimuthal variation of the radiation pattern of the strong motion.

Several attempts have been made in south Balkans for the definition of seismogenic source. Very recently, Papaioannou and Papazachos (1999) used all previous zonation results and relative experience, as well as new, seismotectonic information to separate the south Balkan area in 67 seismogenic sources of shallow earthquakes. For each one of these sources the necessary seismicity parameters were calculated, That is, the parameters a, b, of the Gutenberg and Richter (1944) recurrence relation; the area, S, of the source; the maximum earthquake magnitude, M_{max} and the rate, r, of earthquakes (yearly number of shocks with $M \geq 5.0$). Seven (7) seismogenic sources of intermediate depth earthquakes and their seismicity parameters have been also determined for such earthquakes which occur in the south Aegean area (Papazachos and Papaioannou, 1993).

Anisotropic radiation of the strong motion for each source is adequately described by the high intensity isoseismals, while the isoseismal of intensity I=VIII, in MM scale, defines approximately the rupture (fault) zone (Papazachos et al., 1999). To take into consideration the anisotropic radiation at the source, Papazachos (1992) modeled the high intensity isoseismals by including in the attenuation relations a factor, S, which depends on the ellipticity, e, of the high intensity isoseismals and on the azimuth, • , of the major axis of these isoseismals. Rupture (fault) zones can be also defined by other type of data such as surface fault traces, fault plane solution and spatial distribution of small earthquakes. Therefore, typical values of e and • were calculated for each seismogenic source, by the use of all the available information (isoseismals, fault plane solutions, etc) and the radiation pattern (azimuthal radiation of intensity at the source) was modeled accordingly. Thus, the known Kovesligethy (1906) relation, which has been originally derived for isotropic radiation (circular isoseismals) was modified to

$$I - I_{O\,\min} = n \log\left(S^{1/2} R/h \right) - c(R-h) \qquad (1)$$

where, I_{Omin}, is the apparent epicentral intensity at the direction of the minimum energy radiation (small axis of elliptical isoseismals), R is the hypocentral distance, h is the focal depth, n is the geometrical spreading factor, c is the anelastic attenuation coefficient and

$$S = 1 - e^2 \cos^2(\xi - \varphi) \tag{2}$$

where, e, is the ellipticity of the isoseismals, • is the azimuth of the major axis of the elliptical isoseismals and • is the azimuth of the direction of the site we are studying. It can be shown (Papazachos, 1992) that the Kovesligethy relation (equation 1 without S) is still applied with an equivalent epicentral intensity at each direction, • , which is given by the formula:

$$Io(\varphi) = Io_{\min} + \frac{n}{2} \log S(\varphi) \tag{3}$$

Figure (1) shows the currently obtained results for the Aegean area concerning the definition of seismogenic sources (Papazachos and Papaioannou, 1999), as well as the definition of rupture (fault) zones (Papazachos et al., 1999) which are shown as ellipses. The length and width of the ellipses corresponds to the observed (or theoretically predicted from the earthquake magnitude) length and width of the seismic fault. It can be seen that the available rupture (fault) zones can adequately define the azimuth, • , of the maximum energy radiation in each seismogenic source.

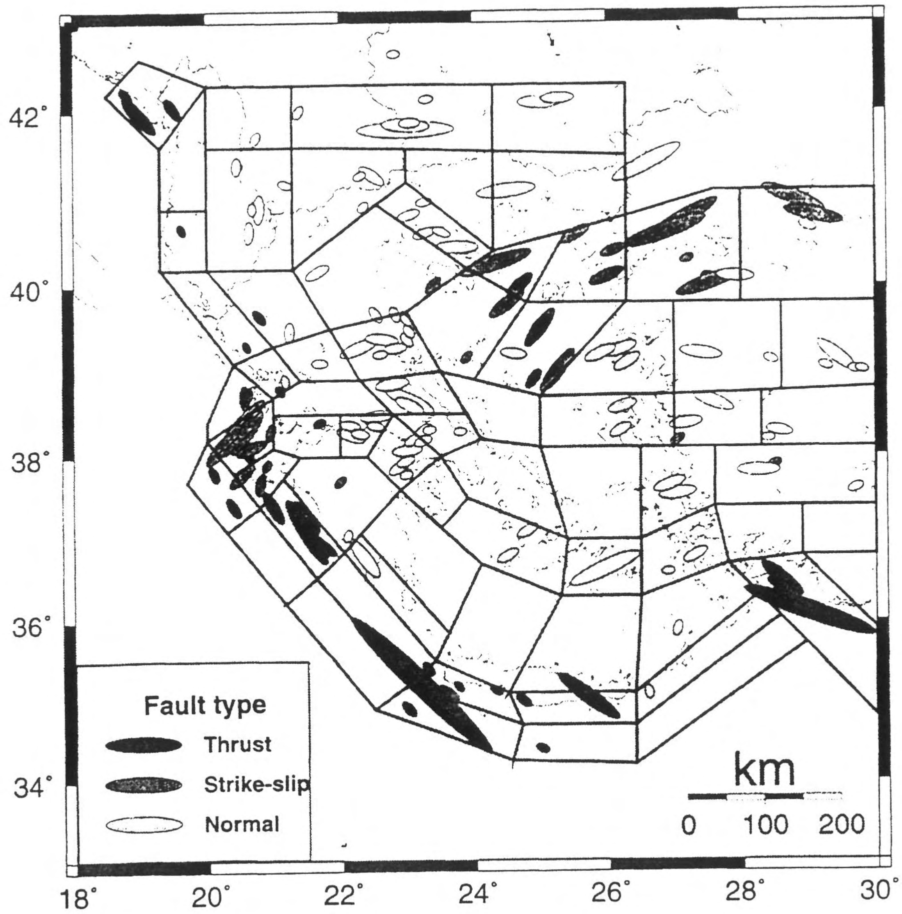

Figure 1. Seismogenic sources and rupture (fault) zones for the Aegean area (Papazachos and Papaioannou, 1999; Papazachos et al., 1999).

3. Attenuation of Strong Seismic Motion

Attenuation relations of strong seismic motion in south Balkans have been proposed for the basic parameters of this motion (ground acceleration a_g, ground velocity u_g, ground displacement d_g) as well as for macroseismic intensity I.

Theodulidis and Papazachos (1992) proposed the following relation for the peak ground acceleration a_g (cm/sec^2) of shallow earthquakes

$$\ln\alpha_g = 1.12M - 1.65\ln(\Delta+15) + 0.41L + 0.71P \qquad (4)$$

where M is the moment magnitude, • the epicentral distance (in km), L a factor for local conditions (L=1 for rock, L=0 for alluvium) and P is a constant with P=0 for the mean value and P=1 for the mean value plus one standard deviation. They also proposed relations of the same form for the ground velocity and ground displacement. On the other hand, Theodulidis (1991) proposed relations of the same form for the southern Aegean intermediate depth earthquakes, by using strong motion records from such earthquakes in other subduction areas of the world.

Papazachos and Papaioannou (1997) proposed the following relation for the attenuation of the macroseismic intensity, I, as a function of epicentral distance, • :

$$I - Io = -3.59\log(\Delta+6) + c \qquad (5)$$

where c depends on the site conditions with an average value of 3.19, when I is in the MM scale and D in km. They also calculated the parameters of the Kovesligethy (1906) relation (n = -3.227, c = -0.0033) so one can use relation (1) or (5). Papazachos and Papaioannou (1997) determined also the following scaling relation between the epicentral intensity I_O and the magnitude M:

$$Io = 1.43M + d \qquad (6)$$

where d varies from country to country (d = -0.93 for Greece, d=0.27 for Albania, d=0.08 for Yugoslavia, d = -0.15 for Bulgaria, and d = -0.22 for Turkey). Papazachos and Theodulidis (1992) determined the following relations:

$$\begin{aligned} \ln\alpha_g &= 0.40 + 0.67I_{MM} \\ \ln u_g &= -3.02 + 0.79I_{MM} \end{aligned} \qquad (7)$$

which can be used to calculate ground acceleration or velocity when macroseismic intensity is known and vice-versa.

If enough data are available for a site (city, town, village) the "average" site conditions can be taken into considerations because the parameter c of relation (5) can be then calculated. Also, differences in the national practices for estimation of macroseismic intensities can be also taken into account because the value of parameter d of relation (6) is known for each country. Attenuation parameters, however, are considered to be constant (n= -3.227, c= -0.0033, etc) which means that an implicit assumption is made that variation of the seismotectonic environment along the wave path do not affect attenuation. To test this assumption, Papazachos and Papaioannou (1998) plotted I-I_O as a function of distance and for two focal depths (h=7km, h=20km) by using data of shallow earthquakes for Greece and by using data from all other Balkan countries separately. It was shown that for both focal depths the difference up to a distance of 120km (up to where damage usually occur) was negligible. It must be noted, however, that this holds only for shallow earthquakes. The attenuation for the seismic waves of intermediate depth earthquakes in the southern Aegean varies much along the wave path.

If we want to take into consideration an anisotropic radiation of the seismic energy at the source, relation (5) is still applied with an equivalent epicentral intensity at each direction, which is given by the relation (3).

4. TIME INDEPENDENT HAZARD

It is now possible to determine time independent hazard at a site, that is, the mean return period, T_m, of a given intensity, I, using a modified version of the EQRISK program (McGuire, 1976), which takes into consideration the seismicity parameters of each seismogenic source (a, b, M_{max}, t), the radiation pattern at the source (relation 3), the attenuation along the path from each source to site and the site effect (relation 5) and variation in the national practice for estimation of the macroseismic intensity (relation 6). This program (Margaris, 1994; Papaioannou and Papazachos, 1999) can be also used for ground acceleration or velocity. For each site a relation of the form

$$I = c_1 \log T_m + c_2 \tag{8}$$

can be determined for each site (Papaioannou and Papazachos, 1999). Then, the probability, P, for the occurrence of intensity I during a time interval • t is given by the relation:

$$P = 1 - \exp\left(-\frac{\Delta t}{T_m}\right) \tag{9}$$

since a Poisson process is assumed in the case of time independent hazard.

5. TIME DEPENDENT HAZARD

Time dependent hazard assessment assumes time dependent seismicity at the seismogenic sources. Several models of time dependent seismicity have been proposed. One such model, which has been tested in several areas, is the regional time and magnitude predictable model (Papazachos and Papaioannou, 1993). According to this model the interevent time, T (in years), between two mainshocks in a seismogenic source is given by the relation:

$$\log T = 0.19 M_{\min} + 0.33 M_P - 0.39 \log m_O + d \tag{10}$$

where M_{min} is the magnitude of the smallest mainshock considered , M_p is the magnitude of the previous mainshock which occurred in the source, m_o is the annual rate of seismic moment and d is a constant which must be determined by the available data concerning the mainshocks of the seismogenic source (Papazachos et al., 1997). The Gutenberg and

Richter relation (1944), which holds for time independent seismicity, can take a similar form to equation (10) but without the term 0.33 M_p.

Papaioannou and Papazachos (1999) modified further the EQRISK program to calculate time dependent hazard in the area of Greece, by taking into consideration relation (10) and assuming a lognormal time distribution for earthquakes with $M \geq 5.5$ instead of a Poisson time distribution, which is assumed in the case of time independent hazard. They calculated the expected macroseismic intensities in 144 sites of Greece during the period 1996-2010. Their results are very reasonable as it is indicated by their comparison with real observations concerning previous periods of the same duration.

Since time dependent hazard assessment is of primary importance for focusing the preparedness measures in special regions where strong earthquake are expected during a certain future time internal, additional time dependent seismicity models must be tried. One such promising model is the one, which is based on seismological observations for an accelerating seismicity in a relatively braid region before large earthquakes as well as on principles of statistical physics. According to this model accelerating seismicity can be explained by a power low and the mainshock is considered as a critical point (Sykes and Jaume, 1990; Bufe and Varnes, 1993; Sornette and Sammis, 1995; Bowman et al., 1998). An attempt was made to identify such preshock (critical) regions in the lithosphere of south Balkans by assuming that these regions have a circular shape. Information on preshocks of large mainshocks ($M \geq 6.0$), which occurred in this region after 1950, were used for this purpose. It is found that the radius, R (in km), of the preshock (critical) region is related with the magnitude of the mainshock by the relation

$$\log R = 0.40M - 0.55 \qquad (11)$$

with a correlation coefficient equal to 0.93 and a root mean square error equal to 0.075. Thus, if a preshock region is identified, its radius can be used to calculate the magnitude of the expected mainshock. Then, the power low relation can be applied to estimate the origin time of the mainshock. There are, however, several problems, which must be solved before such a model can be applied for time dependent hazard assessment.

6. VALIDATION OF THE RESULTS

Estimation of seismic hazard at a site by any model needs further check of the calculated values by using the available observations, due to the existence of uncertainties relating the various steps of such procedure. In order to minimize the uncertainties due to attenuation, we proposed site dependent attenuation relation, using the information of a recently compiled data bank of macroseismic intensities observed from antiquity up to now in almost all broad sites (cities, towns, villages) of the Balkan area (including almost 35000 observations). We also developed an algorithm by which the parameters of relation (8) can be calculated directly from the observed macroseismic intensities and compared with the predicted by the model values. Since common procedures of seismic hazard consider attenuation models that express a "mean" attenuation of the expected strong motion parameters, then observed at the site macroseismic intensities are usually higher than the expected. However, when the model takes into consideration the effect of the shallow sedimentary layer on the strong seismic motion, the calculated by the model and the observed seismic hazard parameters must be comparable.

REFERENCES

Algermissen, S.T., D.M. Perkins, W. Isherwood, D. Gordon, G. Reagor and C. Howard (1976). Seismic risk evaluation of the Balkan region, *Proc. Sem. Seismic Zoning Maps, UNESCO, Skopje,* **2**, 172-240.

Bowman, D.D., G. Ouillon, G.C. Sammis, A. Sornette and D. Sornette (1998). An observational test at the critical earthquake concept, *J. Geophys. Res.* **103**, 24359-24372.

Bufe, C.G. and J.D. Varnes (1993). Predictive modeling of the seismic cycle of the greater San Francisco Bay region, *J. Geophys. Res.* **98**, 9871-9883.

Gutenberg, B. and C. F. Richter (1944). Frequency of earthquakes in California, *Bull. Seism. Soc. Am.* **34**, 185-188.

Cornell, C.A. (1968). Engineering seismic risk analysis, *Bull. Seism. Soc. Am.* **58**, 1503-1606.

Koveslígethy, R. de (1906). A makroszeizmikus rengesek feldolgozasa, *Math. Es. Termeszettudomanyi Ertesito,* **24**, 349-368.

McGuire, R.K. (1976). FORTRAN computer program for seismic risk analysis, *U.S. Geol. Survey, Open-File Rep.*, **77**, 90pp.

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

Margaris, V.N. (1994). Azimuthal dependence of the seismic waves and its influence on the seismic hazard assessment in the area of Greece, *Ph. D. Thesis, Univ. Thessaloniki*, 324pp. (in Greek, with an English abstract).

Papaioannou, Ch. A. (1986). Seismic hazard assessment and long term earthquake prediction in Southern Balkan region, *Proc. 2^{nd} Int. Sem. on Earthquake Prognostics, A. Vogel and K. Brandes (Editors), Berlin*, 223-241.

Papaioannou Ch. A. and B. C. Papazachos (1999). Time independent and time dependent seismic hazard in Greece based on seismogenic sources, *Bull. Seism. Soc. Am.* (in press).

Papazachos, B.C. and Ch. A. Papaioannou (1993). Long-term earthquake prediction in the Aegean area based on a time and magnitude predictable model, *Pure Appl. Geophys.* **140**, 595-612.

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

Papazachos, B.C., E.E. Papadimitriou, G.F. Karakaisis and D.G. Panagiotopoulos (1997). Long term earthquake prediction in the Circum-Pacific convergent belt, *Pure Appl. Geophys.* **149**, 173-217.

Papazachos, B.C., Ch.A. Papaioannou, C.B. Papazachos, and A.S. Savvaidis (1999). Rupture zones and seismic faults of shallow earthquakes in Greece, *Tectonophysics, (in press).*

Papazachos, C.B. (1992). Anisotropic radiation modelling of macroseismic intensities for estimation of the attenuation structure of the upper crust in Greece, *Pure Appl. Geophys.* **138**, 445-469.

Papazachos, C. B. and Ch. A. Papaioannou (1997). Macroseismic field of the Balkan area, *J. of Seismology,* **1**, 181-201.

Papazachos, C. B. and Ch. A. Papaioannou (1998). Further information on the macroseismic field of the Balkan area, *J. of Seismology,* **2**, 363-375.

Sornette, D. and G.C. Sammis (1995). Complex critical exponents from renormalization group theory of earthquakes: Implications for earthquake predictions, *J. Phys. I.,* **5**, 607-619.

Stavrakakis, G. N. and J.E. Papoulia (1990). Prediction of seismic intensities at a site, *Boll. Geof. Teor. Appl.,* **32**, 57-65.

Sykes, L.R. and S. Jaume (1990). Seismic activity on the neighboring faults as a long-term precursor to large earthquakes in the San Francisco Bay area, *"Nature",* **348**, 595-599.

Theodulidis, N.P. (1991). Contribution to the study of strong motion in Greece, *Ph.D. Thesis, Univ. Thessaloniki*, 500pp (in Greek with an English abstract).

Theodulidis, N. P. and B.C. Papazachos (1992). Dependence of strong ground motion on magnitude - distance, site geology and macroseismic intensity for shallow earthquakes in Greece: I, Peak horizontal acceleration, velocity and displacement, *Soil Dyn. Earthq. Eng.*, **11**, 387-402.