ATLAS OF ISOSEISMAL MAPS OF SELECTED GREEK EARTHQUAKES (1956–2003)

Z. Schenková [1], I. Kalogeras [2], V. Schenk [1], R. Pichl [1], M. Kourouzidis [2]
and G. Stavrakakis [2]

[1] Institute of Rock Structure and Mechanics, Academy of Sciences,
CZ-182 09 Praha 8, Czech Republic. E-mail: zdschenk@ irsm.cas.cz

[2] National Observatory of Athens, Geodynamic Institute, P.O.Box 20048,
GR-11810 Athens, Greece. E-mail: i.kalog@ gein.noa.gr

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Macroseismic database of GI NOA

Macroseismic intensity is a useful measure for earthquake effects, which is used in various studies covering a wide range of seismological applications (seismic hazard assessment, attenuation relationships, calculation of magnitude and seismic energy released, focal parameters estimation etc.). Furthermore, it has to be denoted that macroseismic data are the only information describing seismic damage effects of the historical earthquakes for which no instrumental data exist.

Geodynamic Institute of the National Observatory of Athens (GINOA) has collected macroseismic observations since its establishment in 1893 following generally the same procedure. The procedure consists of the following steps: after a moderate or strong earthquake printed questionnaires are directed to local authorities of selected towns and villages looked up with respect to their spatial distribution and the density of population. The completed questionnaires are then graded with respect to the Modified Mercalli (MM) intensity scale (Papazachos et al., 1982; Pappaioannou, 1984) and the assessed macroseismic intensities are published in the GINOA monthly bulletins. For some earthquakes the isoseismal maps drawn by an expert's hand are included in the bulletins.

In the last years Geodynamic Institute updated the procedure of collecting and evaluating macroseismic observations within the frame of various research projects. It develops macroseismic database running under MsAccess that aims to two targets, semi-automatization of the observations collection and manipulation of information connected to the macroseismic intensities (Kalogeras et al., 2004). The questionnaire was improved, including more detailed description of damage without affecting the grading according to the MM intensity scale. Three main tables are included in the database with one-to-many relationships: Table SITE involves administrative information on the municipalities and communities, as well as the coordinates, the dominant surface geology and the reference seismic hazard zone, table QUAKES includes the seismic parameters of strong earthquakes within the area of Greece ($Ms \geq 5.5$) occurred after 1900 and the description of the seismogenic fault and table EFFECT gives the macroseismic intensity observed at each site for each earthquake, the epicentral and hypocentral distances, the azimuth and the peak ground motion, if any. Other tables are incorporated including supplementary information: Tables INFO (photographs, descriptions and bibliography), FLINN (geographical area of sites and epicentres) and COUNTRY (launching a possibility to involve macroseismic observations from other countries). By SQL programming different queries can be applied to combine the parameters included and to attain various relationships, while a visualization manager maps the different information and/or the query results (maps of epicentres, sites, intensities, geology, earthquake hazard, peak ground motions etc).

Isoseismal map drawing

The problem of drawing relative objective isoseismals is a centennial one (Sirovich et al., 2002). There are the differences between contours obtained by various experts. An international experiment (Cecić et al., 1996), when the same macroseismic data sets for a number of European earthquakes were supplied to 16 authors from 11 European countries, describes all these uncertainties. Shebalin (1974), Papazachos et al. (1982) and Papazachos et al. (1997) used approaches that introduced the circular and/or elliptical model in the isoseismal drawing od Greek earthquakes.

During the last decade different geostatistical approaches for the objectivity improvement in isoseismal tracing were proved. Relatively a high attention has been paid to sophisticated computational isoseismal map drawing, mainly two of them: the natural neighbours and the kriging applications. The first one is a concept of computational geometry describing properties of arbitrarily distributed points in any number of dimensions. The second one is a geostatistical gridding method based on the theory of regionalized variables that allows visually appealing maps from irregularly spaced data to be produced.

An algorithm of the natural-neighbour (n-n) coordinates for weighting, interpolating and contouring the irregularly distributed macroseismic observations was proposed by Pettenati et al. (1999) and Sirovich et al. (2002). The authors stated that the n-n isoseismals do not increase the complexity of quantitative source-inversion because of no increase of the number of unknowns in contouring parameters.

Kriging geostatistical gridding method (Cressi, 1990 and 1991; Isaaks and Srivastava, 1998; Burrough and McDonnell, 1998) is based on the theory of regionalized variables that allows visually appealing maps from irregularly spaced data to be produced. Kriging reflects the density distribution of the points, provides an error estimation and confidence interval for every of the unknown points and gives the degree of spatial autocorrelation, modelling in such a way regional trends and local anomalies.

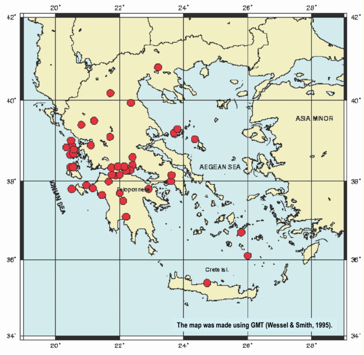
provides an error estimation and confidence interval for every of the unknown points and gives the degree of spatial autocorrelation, modelling in such a way regional trends and local anomalies. In short, kriging is a distance weighting estimation method that takes advantage of the spatial characteristics of the local structure through the variogram function. Kriging algorithm can act either an exact or a smoothing interpolator that allows weights of inter-data spacing, inherent length scale, repeatability and natural anisotropy of the considered data to be assessed and incorporated. The essential kriging parameters are entered into the algorithm via the variogram: the length scale is given by the variogram range (or slope), the data repeatability is specified by the nugget effect and the anisotropy is given by the anisotropy itself.

Kriging options used in the Atlas

were defined on a base of exhaustive analyses and tests. It was decided that the point kriging, contrary to the block kriging which produces a slight data smoothing, estimates the values of the points at the grid nodes that fits better to the observed macroseismic intensities thus all kriging applications carried out below relates to the point kriging. The aim was to assign as much as possible unbiased kriging defaults, i.e. incorporating minimum variable parameters. Thus, the recommended kriging default option (Schenk et al., 2006; Schenková et al., 2006) gives the following default linear variogram function parameters that optimally fitted to macroseismic observations applications: i) to use the no search option - because out data sets contain frequently less than 1000 observation points ii) to introduce the nugget effect $N = 1$ and the linear variogram slope $S = 1$; these values fits to the ratio $N/S = 1$ under that a reasonable smoothing of individual isoseismals exist, and iii) to put anisotropy $A = 1$, because every macroseismic field is represented more or less by a "bell" data distribution on the Earth's surface. For the calculations the kriging method exploits in the SURFER software package (Golden Software Inc, 2004) was used. Essential goal was to apply the kriging default option to different macroseismic field types with respect to a density of observation points, to a range of intensity values and to an earthquake position with respect to a dry land area.

The set of 43 earthquakes included in this atlas is not intended to be a full set of the Greek earthquakes for which macroseismic observations exist. Special care was taken to use data from earthquakes having different characteristics (concerning the magnitude, the number of observations, the region of occurrence), in order for the reliability of kriging method to be tested on various events. Table includes the seismic parameters of the earthquakes of the present Atlas and Figure shows the spatial distribution of the events. For each earthquake exepts of the kriging isoseismal map, a brief description of the earthquake, its effects and related bibliography are included (see below).

Spatial distribution of the earthquakes epicentres included in the Atlas



The map was made using GMT (Wessel & Smith, 1995).

Summary

The Geodynamic Institute NOA collected and evaluated macroseismic observations within the area 33˚N–42˚N and 19˚E–29˚E. The procedure of macroseismic data collection and manipulation with additional information for their interpretation were semiautomatized. The questionnaire was improved including more detailed description of damage without affecting grading according to the MM intensity scale. Easy access to the developed macroseismic database allows 43 earthquakes from period 1956-2003 to be selected and their isoseismal maps to be drawn by kriging method. After exhaustive analyses and tests intensity data the Institute of Rock Structure and Mechanics AS CR within the bilateral Czech-Greek science collaboration defined kriging default option with the aim to assign as much as possible unbiased map drawing, i.e. incorporating minimum variable parameters. The set of 43 isoseismal maps create the substantial part of the atlas of isoseismal map of Greece [ISBN 960-85711-8-9] issued recently. Beside maps the atlas contains a table summarizing seismic parameters of all 43 earthquakes (date, origin time, coordinates, depth, Ms, Imax, number of sites where earthquake was felt, region etc.), map of epicentres, brief description of these earthquakes and their site effects, related bibliography.

List of earthquakes included in the Atlas

No	Date	Time	Latit.	Long.	Depth	M_S	Imax	Region	No of obs.	Source*
1	09 JUL 1956	03:12	36.70	25.80	5	7.5	IX	Aegean Sea	124	COM&PAP
2	15 NOV 1959	17:09	37.80	20.50	5	6.8	VII	Ionian Sea	263	COM&PAP
3	28 AUG 1962	11:00	37.80	22.90	95	6.8	VIII+	Peloponnese	780	COM&PAP
4	23 FEB 1964	22:41	39.20	23.70	10	5.4	VII	Northern Sporades	191	COM&PAP
5	17 JUL 1964	02:34	38.00	23.60	155	6.0	VI	Attiki	456	COM&PAP
6	18 JUL 1964	03:40	36.10	26.00	107	5.3	V	Southern Aegean	85	COM&PAP
7	09 MAR 1965	17:58	39.30	23.80	18	6.1	VIII	Northern Sporades	432	COM&PAP
8	31 MAR 1965	09:48	38.60	22.40	78	6.8	VIII	Central Greece	726	COM&PAP
9	05 APR 1965	03:13	37.70	22.00	34	6.1	X	Peloponnese	446	COM&PAP
10	06 JUL 1965	03:19	38.40	22.40	18	6.3	VIII	Central Greece	379	COM&PAP
11	05 FEB 1966	02:02	39.10	21.70	16	6.2	IX	Central Greece	447	COM&PAP
12	01 SEP 1966	14:23	37.50	22.10	15	6.0	VIII	Peloponnese	307	COM&PAP
13	29 OCT 1966	02:39	38.90	21.10	1	6.0	VIII	Central Greece	309	COM&PAP
14	01 MAY 1967	07:09	39.50	21.20	34	6.4	IX	Epiros	423	COM&PAP
15	04 NOV 1973	15:52	38.90	20.50	13	5.8	VII+	Lefkada island	266	COM&PAP
16	20 JUN 1978	20:03	40.80	23.20	11	6.5	VIII+	Northern Greece	676	COM&PAP
17	10 MAR 1981	15:16	39.40	20.80	32	5.6	VII+	Epiros	230	COM&PAP
18	31 AUG 1985	06:04	39.01	20.48	5	5.3	VII+	Ionian Sea	258	NOA
19	13 SEP 1986	17:25	37.10	22.20	28	6.0	X	Peloponnese	583	NOA
20	24 APR 1988	10:11	38.84	20.33	1	5.0	VI	Ionian Sea	98	NOA
21	18 MAY 1988	05:18	38.35	20.47	1	5.8	VI	Kefalonia island	337	NOA
22	22 MAY 1988	03:44	38.35	20.54	1	5.5	VI	Kefalonia island	149	NOA
23	16 OCT 1988	12:34	37.90	20.96	4	6.0	VIII	NW Peloponnese	293	NOA
24	22 DEC 1988	09:57	38.34	21.75	19	5.0	VI	Peloponnese	94	NOA
25	07 JUN 1989	19:46	37.99	21.65	1	5.3	VII	Peloponnese	140	NOA
26	31 AUG 1989	21:30	38.14	21.87	1	4.8	V+	Peloponnese	102	NOA
27	18 NOV 1992	21:11	38.27	22.33	23	5.7	VI	Gulf of Corinth	465	NOA
28	18 MAR 1993	15.47	38.26	22.20	51	5.4	V	Gulf of Corinth	230	NOA
29	26 MAR 1993	11:58	37.65	21.44	1	5.5	VI+	Peloponnese	190	NOA
30	14 JUL 1993	12:32	38.16	21.76	13	5.6	VII	Peloponnese	306	NOA
31	04 NOV 1993	05:19	38.37	21.94	5	5.1	V+	Gulf of Corinth	170	NOA
32	25 FEB 1994	02:31	38.73	20.58	5	5.8	V+	Lefkada island	170	NOA
33	23 MAY 1994	06:46	35.40	24.73	81	6.1	VI	Crete	210	NOA
34	29 NOV 1994	14:30	38.66	20.46	5	5.4	VI	Ionian Sea	66	NOA
35	01 DEC 1994	07:18	38.69	20.55	5	5.3	V	Lefkada island	39	NOA
36	13 MAY 1995	08:47	40.18	21.71	39	6.6	IX+	Western Macedonia	657	NOA
37	15 JUN 1995	00:16	38.37	22.15	15	6.1	VIII	Gulf of Corinth	409	NOA
38	28 SEP 1995	06:18	38.16	22.00	47	5.3	IV	Peloponnese	79	NOA
39	07 SEP 1999	11:57	38.15	23.62	30	5.9	IX	Attiki	323	NOA
40	26 JUL 2001	00:22	39.05	24.35	19	5.8	VI+	Northern Sporades	297	NOA
41	02 DEC 2002	04:59	37.82	21.16	17	5.8	VI+	NW Peloponnese	201	NOA
42	09 JUN 2003	07:07	39.94	22.35	18	5.5	VII	Thessalia	314	NOA
43	14 AUG 2003	05:15	38.79	20.56	12	6.4	VII	Lefkada island	233	NOA

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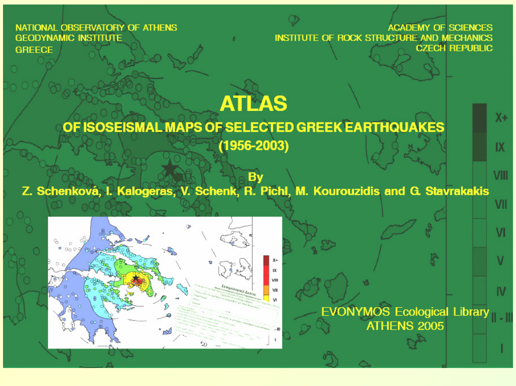

NATIONAL OBSERVATORY OF ATHENS
GEODYNAMIC INSTITUTE
GREECE

ACADEMY OF SCIENCES
INSTITUTE OF ROCK STRUCTURE AND MECHANICS
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OF ISOSEISMAL MAPS OF SELECTED GREEK EARTHQUAKES
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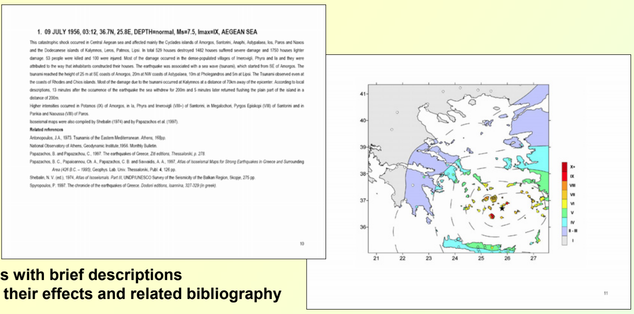

1\. 09 JULY 1956, 03:12, 36.7N, 25.8E, DEPTH=normal, Ms=7.5, Imax=IX, AEGEAN SEA

This catastrophic shock occurred in Central Aegean sea and affected mainly the Cyclades islands of Amorgos, Santorini, Anaphi, Astypalaea, Ios, Paros and Naxos and the Dodecanese islands of Kalymnos, Leros, Patmos, Lipsi. In total 529 houses destroyed 1482 houses suffered severe damage and 1750 houses lighter damage. 53 people were killed and 100 were injured. Most of the damage occurred in the dense-populated villages of Imerovigli, Phyra and Ia and they were attributed to the way that inhabitants constructed their houses. The earthquake was associated with a sea wave (tsunami), which started from SE of Amorgos. The tsunami reached the height of 25 m at SE coasts of Amorgos, 20m at NW coasts of Astypalaea, 10m at Pholegandros and 5m at Lipsi. The Tsunami observed even at the coasts of Rhodes and Chios islands. Most of the damage due to the tsunami occurred at Kalymnos at a distance of 70km away of the epicenter. According to local descriptions, 13 minutes after the occurrence of the earthquake the sea withdrew for 200m and 5 minutes later returned flushing the plain part of the island in a distance of 200m.

Higher intensities occurred in Potamos (IX) of Amorgos, in Ia, Phyra and Imerovigli (VIII+) of Santorini, in Megalochori, Pyrgos Episkopi (VIII) of Santorini and in Parikia and Naoussa (VIII) of Paros.

Isoseismal maps were also compiled by Shebalin (1974) and by Papazachos et al. (1997).

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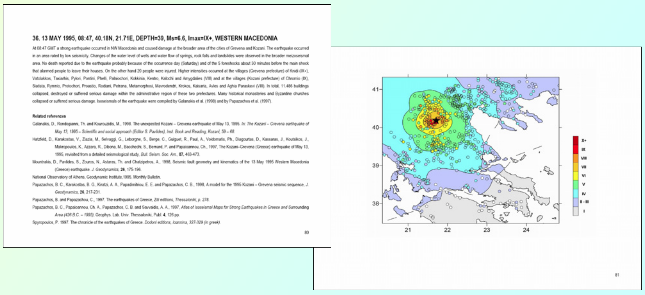
10

Examples
of computed
isoseismal maps with brief descriptions
of earthquakes, their effects and related bibliography

Conclusion

Among various geostatistical gridding approaches the kriging seems to be suitable tool for the computing isoseismal map drawing. A reliability of the kriging method was systematically investigated as far as the optimal kriging default option could be defined for a isoseismal map drawing. It is understandable that certain thresholds in its applications exist as a number of observations per area, an extent of macroseismic intensities observed with respect to the maximum observed intensity, etc. The isoseismal maps of four Greek earthquakes from different parts of Greece were compared with the maps of other investigators (Schenková et al., 2006). The absence of the highest isoseismals in kriging approach depends on an occurrence rate between individual intensity levels. The presented isoseismal maps deliver high efficiency of kriging approach for various levels of observation distribution and their areal density.

Generally, parts inside of the isoseismal maps can be classified as more reliable than the parts outside where isoseismal fields could be shaped in a wrong way because of marginal conditions of the data distribution. Thus, the effectiveness of their reliability has to be assessed individually with respect of applied data. For macroseismic practice a rather important item is that isoseismal maps drawn under the same conditions, i.e. the same level of standardization and homogenization in their drawing were always kept. Moreover, a significance of this Atlas will increase when its isoseismal maps will be used as inputs for the earthquake hazard assessments or for land and urban planning tasks. It is planned to extend the Atlas of the isoseismal maps both for new earthquakes occurred recently and for other historical earthquakes.



36\. 13 MAY 1995, 08:47, 40.18N, 21.71E, DEPTH=39, Ms=6.6, Imax=IX+, WESTERN MACEDONIA

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