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SEISMIC GROUND MOTION ESTIMATES FOR THE M6.1 EARTHQUAKE OF JULY 26, 1963 AT SKOPJE, REPUBLIC OF MACEDONIA

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The identification and characterization of active faults as earthquake sources are essential parts of seismic hazard assessment studies. In the area struck by the 1963 Skopje ($M = 6.1$) earthquake, we define an input fault model according to the proposed source mechanism, the magnitude, and the aftershocks distribution. We test different position for the nucleation point along the fault and we calculate maximum horizontal velocities for a maximum frequency content of 1 Hz. We compare the velocity field with the reported macroseismic intensity one in order to select the fault model that fits the observations best. Our results are in agreement with a seismic source modelled as a 15 × 8 km rectangular plane with magnitude equal to 5.9.

Keywords: macroseismic intensities; strong motion scenarios; synthetic seismograms

Introduction

One of the basic problems associated with the study of the seismic hazard is the estimate of the seismic ground motion due to an earthquake with a given magnitude at a certain distance from a site of interest. This is usually done using attenuation laws and estimating the peak ground acceleration (PGA). Estimates of the ground motion shaking with complete waveforms are done using modelling based on deterministic approaches. An example of such an approach is presented in this study. The scenario earthquake chosen is the July 26, 1963 event, the most destructive earthquake in the recent history of the Republic of Macedonia, whose epicenter was very close to the city of Skopje. Starting from very little seismological information, we define an input fault model according to the aftershock distribution, the magnitude, the proposed source mechanism and the macroseismic intensity distribution. Testing different nucleation points and magnitudes, our fault model is used for computing synthetic seismograms up to 1 Hz at each site where macroseismic intensities are available. We convert the velocity field into a macroseismic intensity one using an empirical relationship. We compute a misfit between calculated intensities and observed ones in order to select the fault model that fits the observations best. The macroseismic data are consistent with a $M = 5.9$ event produced by a 15 × 8 km fault nucleating at 9 km depth, and rupturing bilaterally.

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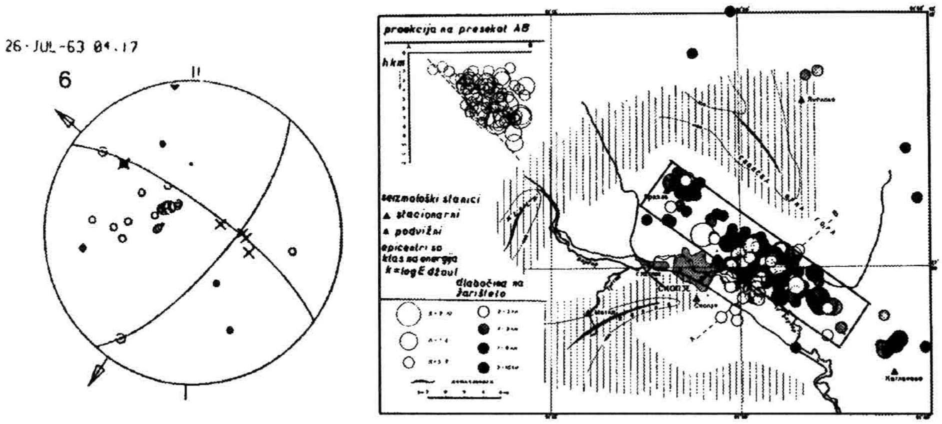


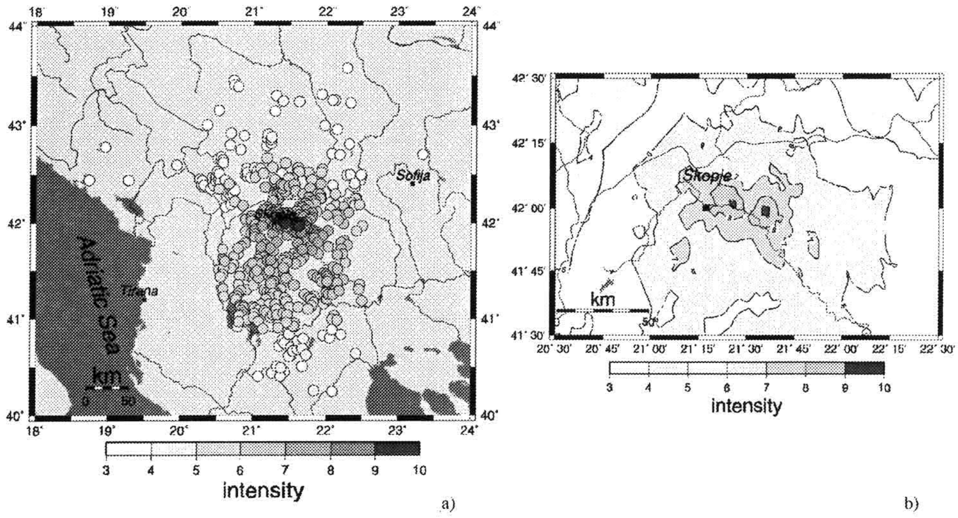
a) b)

Fig. 1. a) Fault plane solution of the Skopje earthquake (from Anderson and Jackson 1987); b) The distribution of the aftershocks (from Pubblication Periodique No. 3 edited by the Observatoire Séismologique de l'Université Skopje, Yugoslavie 1967). The surface projection of the fault plane adopted in the modelling is also shown

The 1963 Skopje event

The Skopje earthquake with a magnitude 6.1 is the most destructive earthquake in the recent history of the Republic of Macedonia. The city of Skopje is situated in the upper part of the Vardar valley and is bordered by high surroundings mountains. The macroseismic epicenter was located in the southern part of Skopje. The event was felt within an area of 200,000 kms^2, with 1070 people killed, 3330 wounded and extensive damage to the city (Arsovski et al. 1968). The epicentral intensity was estimated at IX MCS intensity scale, the released energy at 10^{21} ergs, and the depth of the focus was first put at 6 km (Arsovski et al. 1968).

There are no accelerometric recordings of the 1963 Skopje earthquake. Zatopek (from Arsovski et al. 1968) announced preliminarily the position of the possible slipping surfaces, approximately oriented either NW-SE or NE-SW. According to Sirokova (from Arsovski et al. 1968), the basic parameters of the focal mechanism of the earthquake of July 26, 1963 indicate compression stresses with a trend of ENE-WNW, as well as dilatation stresses along the line NNW-SSE. The possible dislocation slipping surfaces are as follows: first plane, dextral slipping, strike = 15°; second plane, sinistral slipping, strike = 285°. Anderson and Jackson (1987) propose a focal mechanism (Fig. 1a) rather similar to the data by Zatopek (1968). Slejko et al. (1999) report the strike and the plunge of the axes P and T that agree with Anderson and Jackson (1987) and Zatopek (1968).



a) b)

Fig. 2. a) Macroseismic data points of the July 26, 1963 earthquake (from Pekevski, personal communication). b) Contour map zoom of the epicentral area

The macroseismic data

The macroseismic database (Pekevski, personal communication) consists of 668 felt records ranging between intensity degree III and IX (Fig. 2a).

We compute a contour map of the observed intensities, gridding the data and choosing an adequate grid step and a proper tension factor. In this way, the contouring procedure does not distort the intensity distribution. The intensity contours are elongated towards the NW direction, suggesting the strike of the slipping surface being $\theta = 285°$ in accord with the fault plane solutions by Zatopek (1968) and Anderson and Jackson (1987) and with the aftershocks distribution. Moreover there are two high-intensity zones in the epicentral area that could be related to a bilateral rupture propagation of the event.

Finite fault modelling

We compute synthetic seismograms using the Modal Summation method (Panza 1985, Panza and Suhadolc 1987, Florsh et al. 1991, Panza et al. 2001) for a maximum frequency content of 1 Hz, for finite sources (Saraò et al. 1998). Limiting the upper frequency content to 1 Hz allows us to convert the computed ground motion parameters into intensities by means of an empirical relationship (Panza et al. 2001) and in this way to calculate a misfit with the observation. The finite source is modeled as a rectangular plane composed of a grid of point sources with fixed dimension of 0.25×0.25 km, sufficient to avoid space aliasing. The dimensions of the input model that agree with the aftershock distribution (Fig. 1b) are defined according to the proposed magnitude 6.1, using the empirical relationship by Wells and Coppersmith (1994). The seismic source is modelled as a 15 km × 8 km

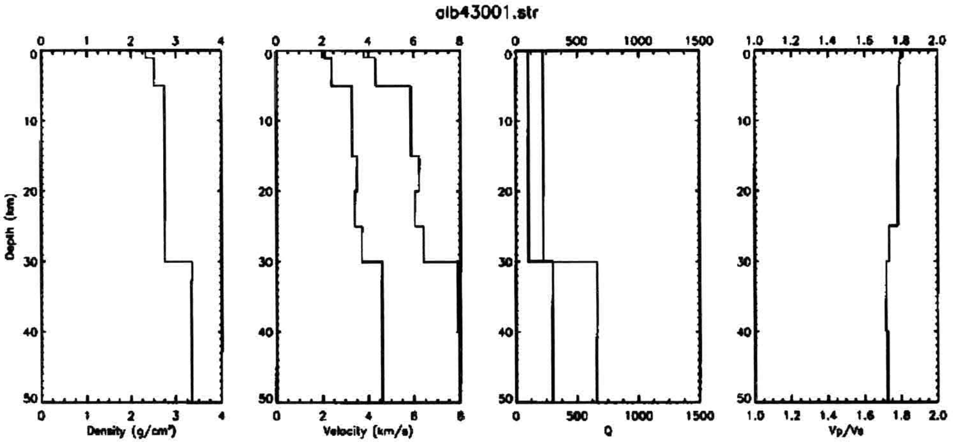


Fig. 3. Density values, P-wave and S-wave velocities and quality factor Q versus depth of the adopted structural model (Muço et al. 2001)

rectangular plane (Fig. 4). The top of the fault is at 2 km depth. The source parameters used in the computation are: strike 298°, dip 79° and rake 22°, according to Anderson and Jackson (1987).

Since at present the information on pertinent structural models for the Republic of Macedonia is very scarce, the structural model used in the calculations is the regional one already adopted for the wider NE Albanian region (Muço et al. 2001).

A constant seismic moment distribution is considered, because of the lack of any information about the slip complexity. To built a more realistic seismic moment distribution, and to avoid possible borders effects, a smoothing following a 2D cosine tapering function is applied (Das and Suhadolc 1996, Saraò et al. 1998, Aoudia 1999, Aoudia et al. 2000). The magnitude has been converted into seismic moment using the relation $\log(M_0) = 1.5(M + 10.7)$, where M_0 is the seismic moment in units of dyne × cm and M is the magnitude (Kanamori 1977). The rupture is taken to propagate at a constant velocity equal the 70% of the shear-wave velocity in the medium. We test different positions for the nucleation point along the fault and different depths.

Following the approach by Fitzko (2002), at each site where macroseismic intensities are reported, we extract from the synthetics the maximum horizontal velocity and we convert it in intensities using the empirical relation by Panza et al. (2001). This regression is in agreement with other macroseismic intensity scales relative to ground motion parameters (e.g. Trifunac and Brady 1975).

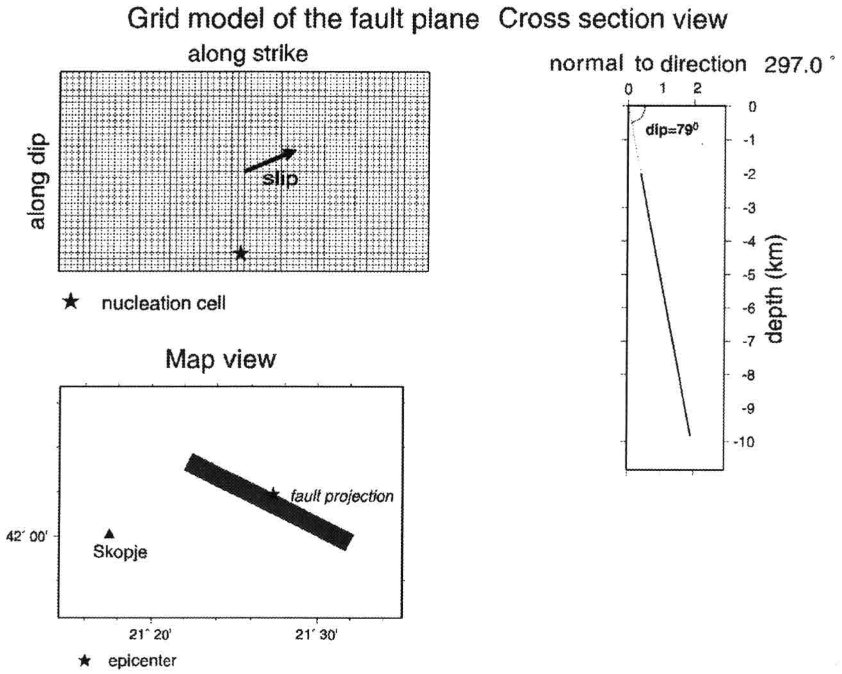


Fig. 4. Fault geometry and map view

Result: misfit between observed and calculated intensities

In this study the geometry of the causative fault for the 1963 Skopje earthquake is estimated from available information on the epicenter location, depth of the source, magnitude and aftershock distribution (Fig. 1b). Several parameters like the depth of the fault plane, the position of the rupture nucleation point on the fault plane and the magnitude are varied in order to obtain the best fit with the macroseismic data points.

It is important to underline that the values of MCS observed intensity lower than V have been removed from the database because for this intensity value the empirical relation is not defined. As a consequence, calculated values of VMAX corresponding to intensities lower than V are not taken into account in the misfit computation, and they are plotted as crosses on the maps of Fig. 5.

When the applied magnitude is equal to 6.1, the values of VMAX obtained by the simulation are too large and consequently the converted intensities are too high compared with the observed ones. This is particularly evident in the areas NNE and SSW of Skopje (Fig. 5a). Additional tests are performed with $M = 6.0$, $M = 5.8$ and $M = 5.9$. When $M = 6.0$, $d_i = (I_{\mathrm{OBS}} - I_{\mathrm{CALC}})_i$ is slightly increased, being still negative at locations NNE and SSW of Skopje (Fig. 5b) whereas the fit is quite good in other zones. With $M = 5.8$, on the other hand, the computed intensities fit well the observations in most of sites distant from the epicenter, whereas they are too small compared to the observations near the source (Fig. 5c). The best fit

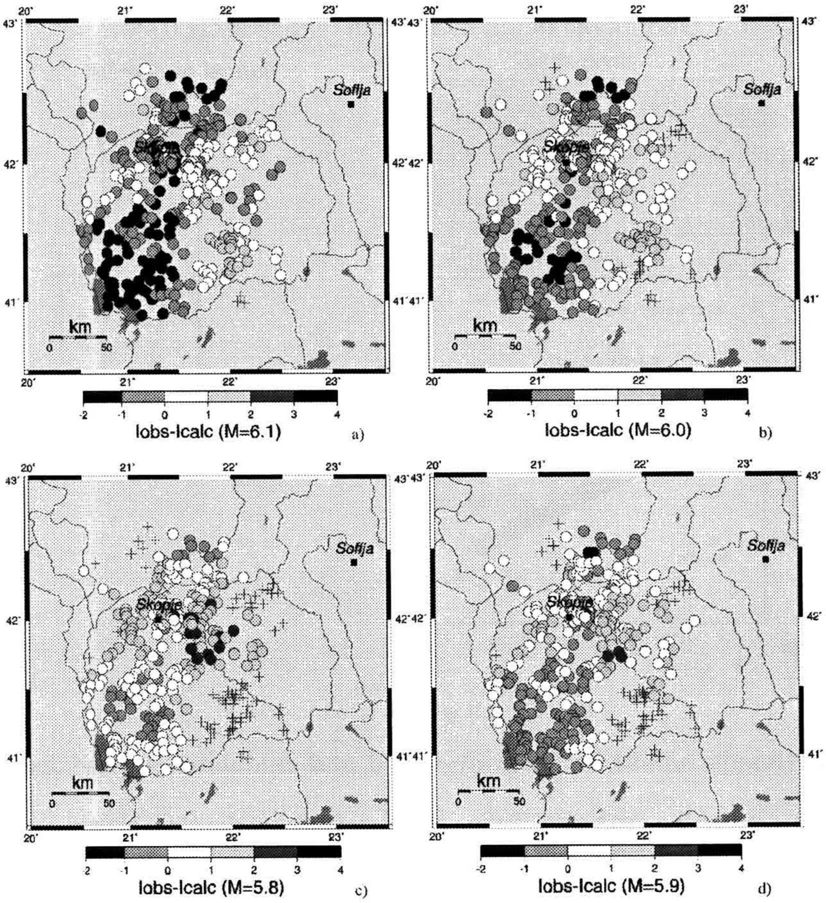


Fig. 5. The misfit between observed and calculated intensities for the magnitude value: a) $M = 6.1$, b) $M = 6.0$, c) $M = 5.8$, d) $M = 5.9$. The values of observed intensity lower than V have been removed from the database (see text). The values of calculated VMAX corresponding to intensities lower than V are plotted as crosses

with the observations is obtained when the applied magnitude is 5.9 (Fig. 5d). The number of sites with $d_i = 2$ is reduced, and in the region around the city of Skopje there are more sites with $d_i = 0$ than in the other cases.

In most of the sites the absolute value of the difference is equal to 1. In particular in the S-SW region of Macedonia ($I_{\mathrm{OBS}} - I_{\mathrm{CALC}}$) is smaller than 1. In the E-SE region of Skopje on the other end this value is larger than 1, with only three sites for which the difference is two degrees on the intensity scale. These three sites are located in the Vardar River Valley that could be responsible for this local amplification. Moreover, in this region most of the sites for which the calculated intensities are smaller than V, plotted as crosses in Fig. 5, are situated. This is also consistent with possible site amplifications affecting the localities in the Vardar River Valley. In Fig. 6b there is a zoom of the epicentral area for the case $M = 5.9$

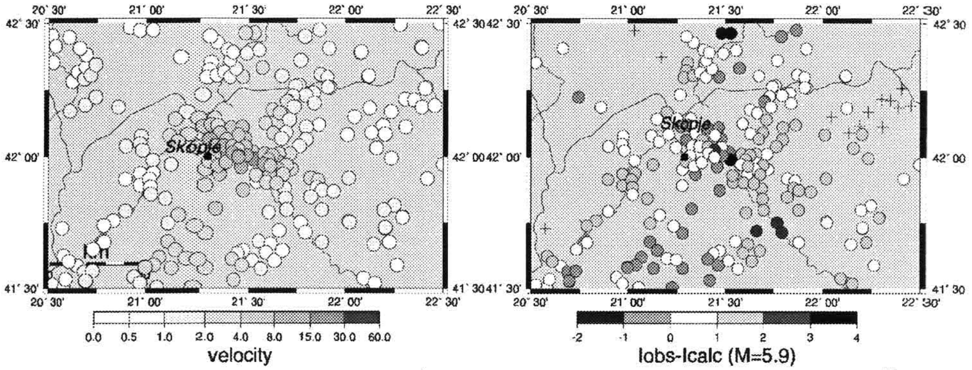


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Fig. 6. Zoom of the epicentral area: a) Maximum horizontal velocities computed at sites belonging to macroseismic database, b) The difference between observed and calculated intensities

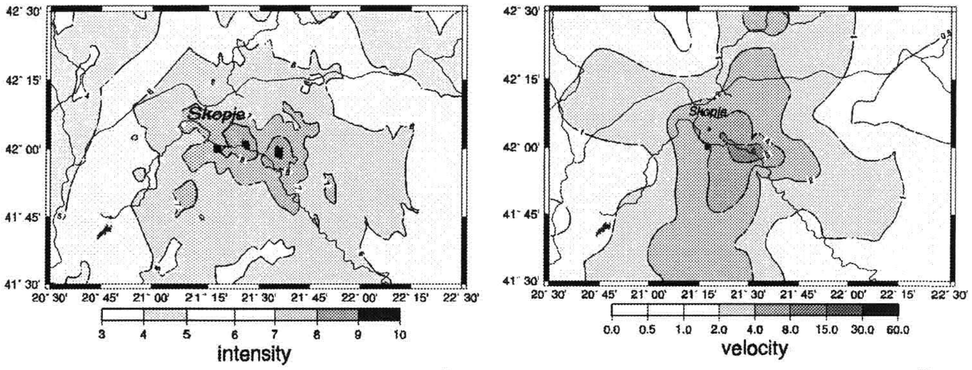

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Fig. 7. Contourmap of the epicentral area: a) the macroseismic felt records, b) the computed horizontal velocities. The rupture propagates bilaterally at 9 km depth

and in Fig. 7b are plotted the calculated velocities as a contour map. The intensity and velocity contours are both elongated in the NW direction, whereas in the zone of the Vardar River Valley to the SE of Skopje, because of possible site effects, to an area of maximum in the observed intensities field corresponds an area of minimum in the calculated velocity field.

Conclusion

The identification and characterization of active faults as earthquake sources are essential parts of seismic hazard assessment studies. The epicenter of the 1963 Skopje earthquake was very close to the city, there were many people killed, a lot of wounded and extensive damage to the urban area. This fact allowed the collection of a large number of macroseismic observations that we have used in this study. On the other hand the available seismological data as well as structural information on the area are poor. Our fault model is built according to the aftershock distribution, the magnitude, the proposed source mechanism and the macroseismic intensity distribution. We compute synthetic seismograms in the finite source approximation in order to determine velocity estimates that best fit the observations. Our results are in agreement with a seismic source modelled as a 15 × 8 km rectangular plane and with a magnitude equal to 5.9. Testing different positions and depths, the top of the fault is put at 2 km depth and the nucleation point at 9 km depth. The rupture is taken to be bilateral. The estimated intensities agree in general well (largely within one intensity degree) with the observed ones. Only in most of the sites lying in the Vardar River Valley, the computed intensities are lower than the observed ones. This could be a consequence of possible site effect amplifications in that area.

Acknowledgements

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