DRMKC Support System

Project

The East Aegean Sea strong earthquake (Mw6.3) of 12 June 2017 and its associated tsunami: a detailed study

Task 2 - Study of the 12 June 2017 Aegean Sea earthquake (Mw6.3)

Deliverable 2

Seismic evaluation of the Mw6.3, 12 June 2017 East Aegean Sea earthquake

Authored by

Dr. G.A. Papadopoulos (NOA)

& Dr. Ceren Özer Sözdinler (KOERI)

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2.1. Introduction

The 12 June 2017 strong earthquake of moment-magnitude \( M_w = 6.3 \) occurred at the sea area to the south of Lesvos Isl. (Greece) (Fig. 2.1) with focal parameters summarized in Table 2.1. It was a shallow event of focal depth around 10 km, which is typical for the area.

This deliverable analyses the focal mechanism and space-time rupture process of the main shock, the characteristics of the aftershock sequence, the field of strong ground motion of the main shock (ground accelerations, shake map) and the damage caused.

Table 2.1. Earthquake parameters determined by various seismological agencies. We inserted preliminary determinations for the reason that they were used by NOA, KOERI and INGV to issue tsunami warnings 10 minutes after the earthquake origin time. Details about the tsunami and the tsunami warning are included in the Deliverable 3 of this study.

<table>
<thead>
<tr>
<th></th>
<th>NOA</th>
<th>KOERI</th>
<th>INGV</th>
<th>EMSC</th>
<th>USGS</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnitude</strong></td>
<td>Mw 6.3</td>
<td>Mw 6.2</td>
<td>Mwp 6.4</td>
<td>Mw 6.3</td>
<td>Mw 6.3</td>
</tr>
<tr>
<td></td>
<td>ML 6.1</td>
<td>ML 6.3</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Depth (km)</strong></td>
<td>11</td>
<td>10</td>
<td>10</td>
<td>9</td>
<td>11.5</td>
</tr>
<tr>
<td><strong>Lat</strong></td>
<td>38.8395°N</td>
<td>38.85°N</td>
<td>38.84°N</td>
<td>38.85°N</td>
<td>38.930°N</td>
</tr>
</tbody>
</table>

References for Table 2.1: http://www.gein.noa.gr/en/recent-alerts;
http://cnt.rm.ingv.it/events?starttime=2017-05-15%2B00%253A00%253A00&endtime=2017-08-13%2B23%253A59%253A59&last_nd=90&minmag=2&maxmag=10&mindepth=-10&maxdepth=1000&minlat=-90&maxlat=90&minlon=-180&maxlon=180&minversion=100&limit=30&orderby=ot-desc&tdmt_flag=-1&lat=0&lon=0&maxradiuskm=-1&wheretype=area&page=16;
https://earthquake.usgs.gov/earthquakes/eventpage/us20009ly0#moment-tensor
2.2. Focal mechanism

The focal mechanism of the earthquake was determined by various seismological institutes (Fig. 2.1, summarized by EMSC). From moment tensor solutions performed by NOA (Fig. 2.2) and KOERI (Fig. 2.3), based on the ISOLA code (Sokos and Zahradnik, 2008), indicated normal faulting. The source parameters calculated are listed in Tables 2.2 and 2.3. The results obtained by NOA and KOERI as well as from other institutes are consistent (Fig. 2.1). The preferred fault plane is the one with strike/dip of $294^\circ/58^\circ$ and $279^\circ/51^\circ$ determined by NOA and KOERI, respectively, from regional seismic records of Greek and Turkish stations. This means that the preferred fault plane strikes NNW and dips to SW. Similar are the solutions obtained by Kiratzi (2018) and Papadimitriou et al. (2018) from waveform modelling inversion utilizing three component broad band and strong motion complete waveforms from regional stations located in Greece and Turkey.

![Figure 2.1. Focal mechanism of the main shock determined by various seismological institutes (summarized by EMSC).](image-url)
To explain why the above fault plane is the preferred one we should take into account the seismotectonic setting of the area. The North Aegean Sea (NAS) is characterized by high seismicity which is due to the westwards branching of the major right-lateral North Anatolian Fault (e.g. Goldsworthy et al., 2002; Papadopoulos et al., 2002). Right-lateral strike-slip is the predominant faulting style associated with large NAS earthquakes as inferred from fault plane solutions (e.g. Taymaz et al., 1991) and surface fault-traces identified during post-event field surveys (Pavlides and Tranos, 1991). However, tectonic basins are formed between the strike-slip segments and are controlled by normal faults trending either NE-SW or NW-SE (e.g. Koukouvelas and Aydin, 2002). The southern coast of Lesvos Isl. is a good example of a basin controlled by normal faults trending NW-SE as concluded by geomorphological and tectonic observations (Soulakellis et al. 2006; Vacchi et al. 2012).

**Table 2.2.** Source parameters of the main shock obtained from the moment tensor solution performed by NOA.

- **Origin Time:** 12/06/2017 12:28:38 (GMT)
- **Latitude:** 38.8395 N
- **Longitude:** 26.3695 E
- **Focal Depth:** 8 Km
- **Mw:** 6.3; **Mo:** $3.321e+18$ Nm

**Table 2.3.** Source parameters of the main shock obtained from the moment tensor solution performed by KOERI.

- **Origin Time:** 12/06/2017 12:28:38 (GMT)
- **Latitude:** 38.85 N
- **Longitude:** 26.25 E
- **Focal Depth:** 10 Km
- **Mw:** 6.3; **Mo:** $3.553e+18$ Nm
Figure 2.2. Moment tensor solution of the main shock performed by NOA.

Figure 2.3. Moment tensor solution of the main shock performed by KOERI.
2.3. Rupture process

For the investigation of the main shock rupture history two different approaches were published so far but both are based on inversion of seismic waveform modelling. The first approach was elaborated by Dr A. Agalos (NOA) in collaboration with the first author of this report and was published in the joint report produced by Greek, Turkish and JRC scientists (Annunziato et al., 2017; https://goo.gl/hvju4q). This approach utilized P-wave records at teleseismic distances ranging from 30° to 90°. On the contrary, the second approach was based on regional records from Greek and Turkish stations (Kiratzi, 2018).

The first approach followed the kinematic finite-fault inversion scheme of Hartzell and Heaton (1983) and Mendoza and Hartzell (2013), which is a non-negative, least squares inversion method. A discretized to uniform cells (sub-faults) rectangular fault plane was constructed and each point source response was computed with a code based on the generalized ray theory (Langston and Helmberger, 1975) using an appropriate for the area velocity model (Karagianni et al., 2005). The synthetics were constructed by following the technique discussed by Heaton (1982). The calculated elementary synthetics were convolved with an attenuation operation under the assumption that t* = 1 sec; t* is the attenuation parameter of teleseismic body waves that represents the total body wave travel time divided by Q along the ray path for P waves (Stein and Wysession, 2003).

In order to retrieve the co-seismic slip model from the inversion of P waves recorded at teleseismic distances, that is from 30° to 90°, waveform data from 30 stations with good azimuthal coverage (Fig. 2.4) were collected and analyzed. The waveform data were downloaded from the IRIS Data Management Center (i.e. data from GSN, II, IU and G digital networks were used) using the Wilber 3 application. The waveforms were band-pass filtered
between 0.03 and 0.08 Hz using a Butterworth filter, re-sampled to 0.2 samples/sec and finally integrated in time to obtain displacements. All waveforms were pre-processed before the inversion with the aim to remove the mean offset and instrument response. The fit between data and synthetics is shown in the Appendix of this deliverable (Fig. A1).

![Figure 2.4. Teleseismic stations at distances from 30° to 90° for which waveform data were analyzed.](image)

Regarding the fault parameterization, several values of source velocity were examined, varying from 2.6 to 3.3 km/sec, while various values for rise time, fault dimensions and time lag were tested. The source of the elementary synthetics was taken as of trapezoidal shape and the width of the source was chosen to be short enough (0.3 sec) compared to the total rise time on the fault. The fault examined, whose dimensions were set to 27 km long and 15 km deep, was discretized by 108 sub-faults, 18 of them along strike and 6 along dip.

For the kinematic inversion of the earthquake we adopted fault strike of 114° from the CMT/HARVARD focal mechanism taking the nodal plane with strike NW-SE and dipping to SW. The fault strike was fixed to fit the tectonics of the faults in the area and inversions were performed by changing the dip from
minimum 35° to maximum 55°. The optimum were obtained using fault dip of 37° which, however, is lower than the dip of 50° found in the CMT solution. In order to make the rake vary upon the fault we followed the suggestion by Hartzell et al. (1996) and calculated the synthetics twice varying ±45° from the CMT rake (-82°) using six time windows for the inversion process. The parameters used for, and obtained by, the inversion procedure for each one of the three cases are listed in Table 2.4.

Table 2.4. Fault parameters used or retrieved from the inversion. Symbol key: L=fault length, W=fault width, v=rupture velocity, t=rise time, h=focal depth, Mo=seismic moment, Mw=moment magnitude.

<table>
<thead>
<tr>
<th>Date</th>
<th>L (km)</th>
<th>W (km)</th>
<th>v (km/sec)</th>
<th>t (sec)</th>
<th>h (km)</th>
<th>Rake range</th>
<th>Strike/Dip</th>
<th>Mo (Nm)</th>
<th>Mw</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 June 2017</td>
<td>27</td>
<td>15</td>
<td>3.0</td>
<td>0.3</td>
<td>12</td>
<td>-37 to -127</td>
<td>114°/37°</td>
<td>3.8×10^{18}</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The co-seismic slip distribution of the earthquake, representing the movement of the hanging wall with respect to the foot wall is illustrated in Figure 2.5. The time evolution of slip is presented in each case by 6 snaps using nearly 1.25 sec intervals. The slip distribution is smooth as a 2D cone shaped filter was applied. The simplest solution presented is the one succeeded using a trial-and-error process that balances fitting the data with smoothing and minimizing the slip (Mendoza and Hartzell, 2013); the Residual Norm \(||Ax-b|||) was applied, where A is the sub-fault synthetics matrix, b is the matrix of observations and x is the solution vector containing the slip required to reproduce the observations.
Figure 2.5. Seismic slip history for the Lesvos earthquake of 12 June 2017 in 6 snaps using time intervals of ~ 1.25 sec.

The rupture history of the 12 June 2017 Lesvos earthquake (Fig. 2.5) shows a bilateral propagation mode with upwards rupture directivity. The seismic moment calculated was found \(3.8 \times 10^{18}\) Nm, which corresponds to moment magnitude Mw6.3. This is consistent with the seismic moment calculated by NOA and KOERI. The earthquake rupture had a total duration of ~7 sec. The rupture started at depth of 12 km and evolved up-dip with a rupture velocity of 3 km/sec. The maximum co-seismic slip calculated was ~0.9-1.0 m close to the hypocenter at depth of 11 km. The total rupture had a length of nearly 20 km and the seismic slip was mainly concentrated at depths between 3 and 14 km with seismic slip ranging from 0 to 10 cm across the Earth’s surface.
However, the main rupture area was found of ~11 km in length and of ~6 km in width. According to our inversion and taking into account the dip of the rupture the southeast coastal areas of Lesvos at the northwest from the epicenter were the ones where the small values of slip reached the surface.

The source time function (Fig. 2.6) indicates that the maximum peak of seismic moment release occurred ~3 sec after the rupture initiation, which may represent the main asperity that ruptured. Around the 4th sec of rupture a second, smaller rupture area (asperity) appeared at depth of ~8 km to the NW and upwards of the main rupture event. The overall picture indicates rupture directivity towards NW from the source (Fig. 2.7) where the highest earthquake impact in terms of building damage was observed.

**Figure 2.6.** Source time function of the Lesvos earthquake of 12 June 2017.

**Figure 2.7.** Surface projection of the slip in m.
Slip distribution was obtained by the second approach which was based on modeling through the waveform inversion of regional seismic records (Kiratzi, 2018) (Fig. 2.8). The results indicated a unilateral rupture propagation which makes a difference with respect to the first approach that showed a bilateral propagation, although both approaches are consistent in that the predominant propagation occurred towards NW.

**Figure 2.8** (after Kiratzi, 2018). Slip imaged onto the south dipping plane of the main shock (left), alongside the moment rate function (right). Surface projection of slip and of the aftershocks (down).
2.3 Aftershock sequence

The main shock of 12 June 2017 was followed by intense aftershock activity which continued with low frequency until writing these lines (early March 2018). The largest aftershock of Mw5.3 occurred on 17th June 2017. A cross-section of the aftershock foci (Fig. 2.9) indicates that very likely the fault plane dips to SW as already suggested from the regional tectonics of the area. Most aftershocks were of normal faulting type, i.e. similar to the one of the main shock (Fig. 2.10), but some others, including the strongest aftershock (Figs. 2.10, 2.11), were found to have strike-slip mechanism.

Table 2.5. Source parameters of the largest aftershock obtained from the moment tensor solution performed by NOA.

<table>
<thead>
<tr>
<th>Origin Time</th>
<th>17/06/2017 19:50:05 (GMT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Latitude</td>
<td>38.8497 N</td>
</tr>
<tr>
<td>Longitude</td>
<td>26.4302 E</td>
</tr>
<tr>
<td>Focal Depth</td>
<td>8 Km</td>
</tr>
<tr>
<td>Mw</td>
<td>5.3</td>
</tr>
<tr>
<td>Mo</td>
<td>9.826e+16 Nm</td>
</tr>
</tbody>
</table>

Figure 2.9. Cross-section of the aftershock seismicity recorded up to 5 July 2017.
Figure 2.10. Epicenter plot of the 12 June 2017 main shock (Mw6.3) and its aftershocks recorded in the submarine basin to the south of Lesvos up to 5 July 2017. Beach-balls represent fault-plane solutions. Seismicity data and fault-plane solutions were produced by the Institute of Geodynamics, National Observatory of Athens (http://bbnet.gein.noa.gr/HL/). AA’ is the cross-section used in Fig 2.12.
2.4 Strong ground motion (ground accelerations, shake map)

From preliminary reports (ITSAC 2017; AFAD 2017) it results that the Peak Ground Acceleration (PGA) values, $a$, were recorded in Mytilene, capital city of Lesvos Isl. ($a=0.07 \text{ g}$, E-W component, epicentral distance $\Delta=35 \text{ km}$) and in Foca, W. Turkey ($a=0.06 \text{ g}$, E-W component, $\Delta=44 \text{ km}$). The ground acceleration distribution in western Turkey is shown in the map of Figure 2.12. In the near-field domain the ground acceleration certainly was higher but no records are available. From a simulation of the ground motion (ITSAC, 2017) it comes out that, in Plomari, SE Lesvos Isl., in bedrock conditions and for anisotropic seismic energy propagation the theoretical PGA is $200 \text{ cm/s}^2$ (see also simulation produced by the University of Athens (Fig. 2.13).
**Figure 2.12.** Distribution of Turkish accelerometric stations that recorded the strong ground motion of the 12 June 2017 main shock at epicentral distances $\leq 100$ km (source AFAD, 2017).

**Figure 2.13.** Image prepared by the University of Athens, that confirms that the largest PGA occurred in the south-eastern part of the island, similar in the Shake Map by USGS.
2.5 Damage field

From official post-event building inspections performed by corps of civil engineers of the Natural Disasters Rehabilitation Directorate, Ministry of Infrastructure, Greece, one may conclude that the main shock of 12 June 2017 caused considerable damage only in the southeast side of Lesvos. In Vrissa village one person was killed and several injured. We assigned seismic intensity of VII-VIII degree (MM) to the villages of Akrasi, Ampeliko, Polichnitos, Stavros and Vrissa. Less intensity of VI-VII degree (MM) was assigned to other villages and towns of SE Lesvos. Minor damage was reported from other localities of Lesvos and Chios islands. The damage field is illustrated in Fig. 2.14 while some characteristic damage pictures can be seen in Fig. 2.15.

![Map of Mw 6.3 Plomari Earthquake of 12 June 2017 - Damage Assessment](image)

**Figure 2.14.** Impact of the event and damage field (source JRC report, Annunziato et al., 2017).
Figure 2.15. Damage in village Vrissa after the 12 June 2017 main shock.
2.6 Conclusions

The 12 June 2017 earthquake of Mw6.3 has been a typical shallow seismic event for the area of Greece and W. Turkey. In fact, in this area statistically at least one shallow earthquake of magnitude 6 or larger occur annually as an average. At all evidence the focal mechanism was normal with the fault plane striking NNW and dipping SW.

Aftershock activity followed the main shock for several months. The strongest event (Mw5.3), however, occurred on 17th June 2017. Most of the aftershocks had focal mechanism similar to that of the main shock. Few others, however, including the strongest aftershock, were of strike-slip faulting. This could be interpreted by the possible activation of secondary faults of strike-slip type.

The main shock rupture process determined by the inversion of teleseismic P waveforms indicated bilateral slip propagation with strong directivity towards NW. On the contrary, waveform inversion of regional seismic records showed unilateral rupture but a directivity towards NNW.

The strong motion field is not well understood for the reason that no accelerometric records are available from the near-field domain, i.e. from SE Lesvos Isl. simulation results showed that the theoretical peak ground acceleration there should be about 200 cm/s². In that area occurred the main damage with the intensity estimated at the level of VII-VIII degree (MM).

Acknowledgments

We thank Dr Marinos Charalampakis for helping us with the preparation of figures 2.9 and 2.10. We are thankful to Mr Paraschos Vassouris, Lesvos Fire Brigade, for providing us the damage pictures in Fig. 2.15.
References


Appendix

Figure A1. Fit between P-wave records and synthetics.