The ShakeMap at the Instituto de Meteorologia

C. Marreiros & F. Carrilho
Instituto de Meteorologia, I.P., Lisboa, Portugal

15 WCEE
LISBOA 2012

SUMMARY:
The ShakeMap is a system designed for automatically generate ground shaking and instrumental derived intensity maps (shakemaps) in the minutes following an earthquake. The information on the level of ground shaking and sites of strongest shaking after a damaging earthquake is important for emergency response.
Since 2008, the Instituto de Meteorologia, I.P. (IM), has implemented the ShakeMap software package provided by U.S. Geological Survey (USGS), in order to obtain reliable shakemaps for Portugal mainland.
The recent developments in the seismic monitoring allows more and more instrumental data to became available in near-real time, making it possible to rapidly evaluate source parameters and measure peak ground motion values. This information combined with specific attenuation laws and site corrections based on geology for Portugal mainland makes it possible to rapidly obtain constrained shakemaps.
This work reports the ongoing improvements of ShakeMap in the Portuguese seismic network. Some examples of applications are presented.

Keywords: ShakeMap, ground shaking maps, instrumental intensity

1. INTRODUCTION

The Instituto de Meteorologia has implemented a new computational tool, the ShakeMap, which allows to make quick estimates of macroseismic effects.

The ShakeMap combines instrumental measurements of shaking with information about local geology and earthquake location and magnitude to estimate shaking variations throughout a geographic area (Wald *et al.*, 2005).

ShakeMap generates a set of data files and maps that provide information about various aspects associated with the ground shaking, such as the map of spatial distribution of seismic intensity (instrumental intensity). The instrumental intensity map uses a color code to display the severity of shaking, which allows easily to relate the recorded ground motion with the perceptible shaking level and the distribution of potential damages. Maps of distribution of peak acceleration (PGA) and peak velocity (PGV) are also generated. These maps identify the area affected by the earthquake and estimate the severity of ground shaking providing important information for emergency response planning and for the general public.

Since 1997, shakemaps are made available, via internet, on a routine basis for Southern California by the USGS (Wald *et al*., 1999). Nowadays, the ShakeMap system is installed in other regions of United States and other countries, such as Italy, Switzerland, etc.

Currently, in the Portuguese seismological service the ShakeMap is fully operational and it generates near real-time shakemaps for Portugal mainland.

The ShakeMap can also be used to generate ground motions scenarios for hypothetical large earthquakes.

Although the ShakeMap has been developed with portability in mind (Wald *et al.*, 2005), is necessary to calibrate the system with some regional specifications. To implement the system for Portugal mainland region we added some specific information, such as: 1) distance attenuation relations – ground motion prediction equations (GMPE), that relate PGA and PGV with the epicentre distance and magnitude, proposed by Miranda (*personal communication*); 2) geology and site conditions – site corrections derived from geological information; ground motion intensity conversion equations (GMICE) - relations between Modified Mercalli intensity values (I_{mm}) and PGA or PGV [derived from Atkinson and Kaka (2007) and Wald *et al* (1999)].

ShakeMap application to earthquakes that recently occurred in Portugal mainland region, shows results consistent with the macroseismic observations.

Finally, it should be noted the important advantage that this system provides relatively to the classic scenarios generators, which consists in near real-time integration of instrumental measurements, allowing to generate a more realistic macroseismic field, particularly in the near field domain.

2. IMPLEMENTATION OF SHAKEMAP AT IM

The ShakeMap system is a collection of software tools, most of them written in the PERL programming language. These programs run sequentially to produce data files (e.g. ASCII and XML files), ground motion maps (PostScript and JPEG files) and Web pages.

This system is built from freely available open-source software packages: Linux operating system; a collection of PERL modules; MySQL server used as data base; Generic Mapping Tools (GMT) [Wessel & Smith, 2004] to produce maps; ImageMagick and Ghosthscript to convert file format; etc.

At IM the ShakeMap (version 3.2) was implemented on a PC-Linux platform. It was adapted to the Portugal mainland region, and implemented in order to receive and process instrumental measurements made at the stations of the Portuguese seismic network.

The principal elements of IM ShakeMap system, are: 1) input from the Portuguese seismic network that provides the basic earthquake source parameters (location and magnitude) and the ground motion parameters measured at each station (PGA and PGV); 2) estimations and interpolations of peak ground motions obtained from empirical GMPE and site corrections to Portugal mainland region; 3) instrumental intensity obtained from empirical GMICE that relate seismic intensities of Modified Mercalli scale and PGA / PGV values.

A schematic overview of the ShakeMap processing system at IM is provided in Figure 2.1.

In order to link the instrumental data base to ShakeMap, it was developed and implemented an interface (Seisan2ShakeMap) to the seismic analysis and processing system (SEISAN) used at IM. In addition, it was necessary to change some of PERL modules, to introduce new functionalities including the automatic definition of the area for shakemap generation, implementation of GMPE and GMICE, etc.

The system allows to generate maps of the estimated seismic intensity obtained from instrumental data, contour maps of PGA, PGV and spectral acceleration, grids of points with associated amplitude values of shaking parameters, Geographic Information System (GIS) files and other products for specific users.

At the seismic monitoring system of IM the earthquakes are detected automatically making it possible to get the basic parameters of relevant seismic events (evaluated by the maximum of theoretical intensity in the urban areas near the epicentre) in less than four minutes after the registration of the Pwave at the nearest seismic station. Then, the instrumental measurement of PGA and PGV are made automatically on the seismic records, input files for ShakeMap (Seisan2ShakeMap) are prepared and procedures for shakemaps generation are launched.

The resulting maps and other files are organized in a database and delivered to a local server. In addition, when an event is processed the system generates a collection of web pages where the main products generated are displayed (currently, is available only at IM intranet).

These maps are being made, typically within 5 to 7 minutes from the event record at seismic network.

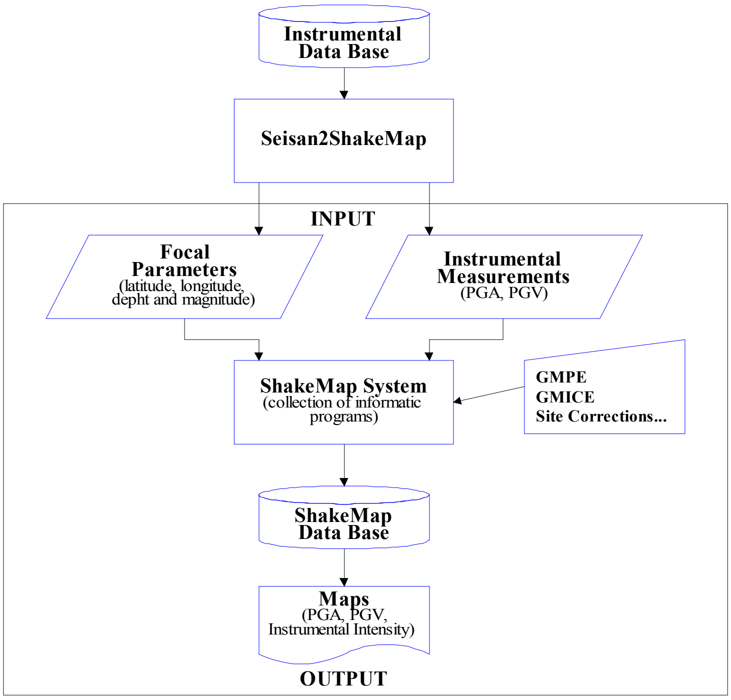

Figure 2.1. Simplified ShakeMap flowchart at IM.

In late 2009, USGS released a new version (V3.5) of ShakeMap software which has new features. Improved ShakeMap interpolation algorithms were introduced, allowing a natural combination of observed ground motions and intensities with estimated peak ground motions, weighted proportionally to the inverse of their uncertainties (Worden *et al*., 2010).

Presently, at IM we are working in the implementation of the new version of ShakeMap software, which is now testing.

2.1. Ground Motion Prediction Equations

The regional GMPE or attenuation relations are fundamental to estimate ground motion at sites where there is no available instrumental measurements.

The GMPE expressed as PGA, that we use for Portugal mainland, relates the ground acceleration, a (%g), to epicentre distance, R (km) and magnitude, M, was proposed by Miranda (*personal communication*) and is valid for Imm < V.

Figure 2.2. shows the regional GMPE expressed as PGA (%g) applied to 6 earthquakes of magnitudes: 3,9ML; 4,0ML; 4,1ML; 4,8ML and 6,0ML. The instrumental measurements for each earthquake are also shown. There is a good agreement between the theoretical values and the observed values for the

two earthquakes of higher magnitude (4,8ML [2008-01-11] and 6,0ML [2007-02-12]). For the earthquake that occurred on 2009-12-17, located about 100 km offshore SW C.S.Vicente, the theoretical values are slightly higher than the observed values. The best fit between theoretical and observed values is obtained for ML = 5,8. It should be noted that in the case of this earthquake the seismic moment magnitude computed by CMT was 5,6MW. For the three earthquakes of lower magnitude (3,9ML, 4,0ML and 4,1ML) the decay of theoretical curve agrees with the observed data distribution, but there is a scaling problem. In these cases, it is necessary to fit the theoretical curve to the observed data, which is done automatically by the software ShakeMap, taking the observed data from the first 150 km.

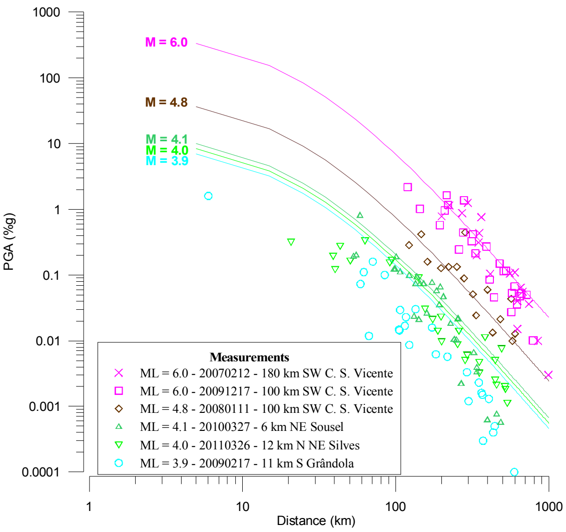

Figure 2.2. Attenuation relations expressed as PGA (for Imm < V), determined using the relation proposed by Miranda (personal communication). The symbols represent the values of PGA (%g) observed for each earthquake listed in the legend at bottom left.

The GMPE expressed as PGV relates the ground velocity, v (cm/s), to the epicentre distance, R (km) and magnitude, M, was proposed by Miranda (*personal communication*) and is valid for Imm > VII.

2.2. Site Conditions

The site conditions or site effects play an important role in the generation of shakemaps, particularly where the network of stations is sparse and fewer data are available. At sites where the instrumental measurements are not available, the ground motion parameters are estimated from empirical GMPE and amplification factors dependent on the geology, for different type of soils.

To obtain reliable maps of ground motion distribution and instrumental intensity it is fundamental to incorporate in the ShakeMap system a realistic model of ground shaking amplifications induced by geology (site conditions or site effects).

The IM ShakeMap incorporates a uniformly spaced grid of site conditions for Portugal mainland region. The site corrections relies on the assignment of site amplification factors determined using a reference velocity, V_s^{30} (the average S-wave velocity values down to 30 m). To obtain site amplification factors we apply Borcherdt (1994) relation for site amplification factors and V_s^{30}.

To address the site condition in Portugal mainland, we have used initially a V_s^{30} classification derived from topography, according to the methodology proposed by Wald & Allen (2007). More recently, we have implemented a classification based on the 1:1000000 geology map of Portugal compiled and published by the "Laboratório Nacional de Energia e Geologia (LNEG)". Since 2011, it has been possible to produce shakemaps with local conditions derived from geology.

The Figure 2.3. shows the results of the ShakeMap application to an earthquake that occurred on 2009-02-17, located 11 km south of Grândola, with magnitude 3,9ML, with site conditions derived from topography [(a) and (c)] and geology [(b) and (d)]. The maps of figures (a) and (b) show the distribution of instrumental intensity estimated by ShakeMap. The maps show the ground shaking converted to color-coded seismic intensity. These maps highlight the strongest shaking region (near Grândola) and the variation of the perceiving shaking level. The two maps do not vary significantly. The earthquake was felt with intensity III-IV (Imm) in the epicentre region (near Grândola) while in Santiago do Cacém and Sines it was felt with lower intensity. The PGA map with site conditions derived from geology has the most irregular contours.

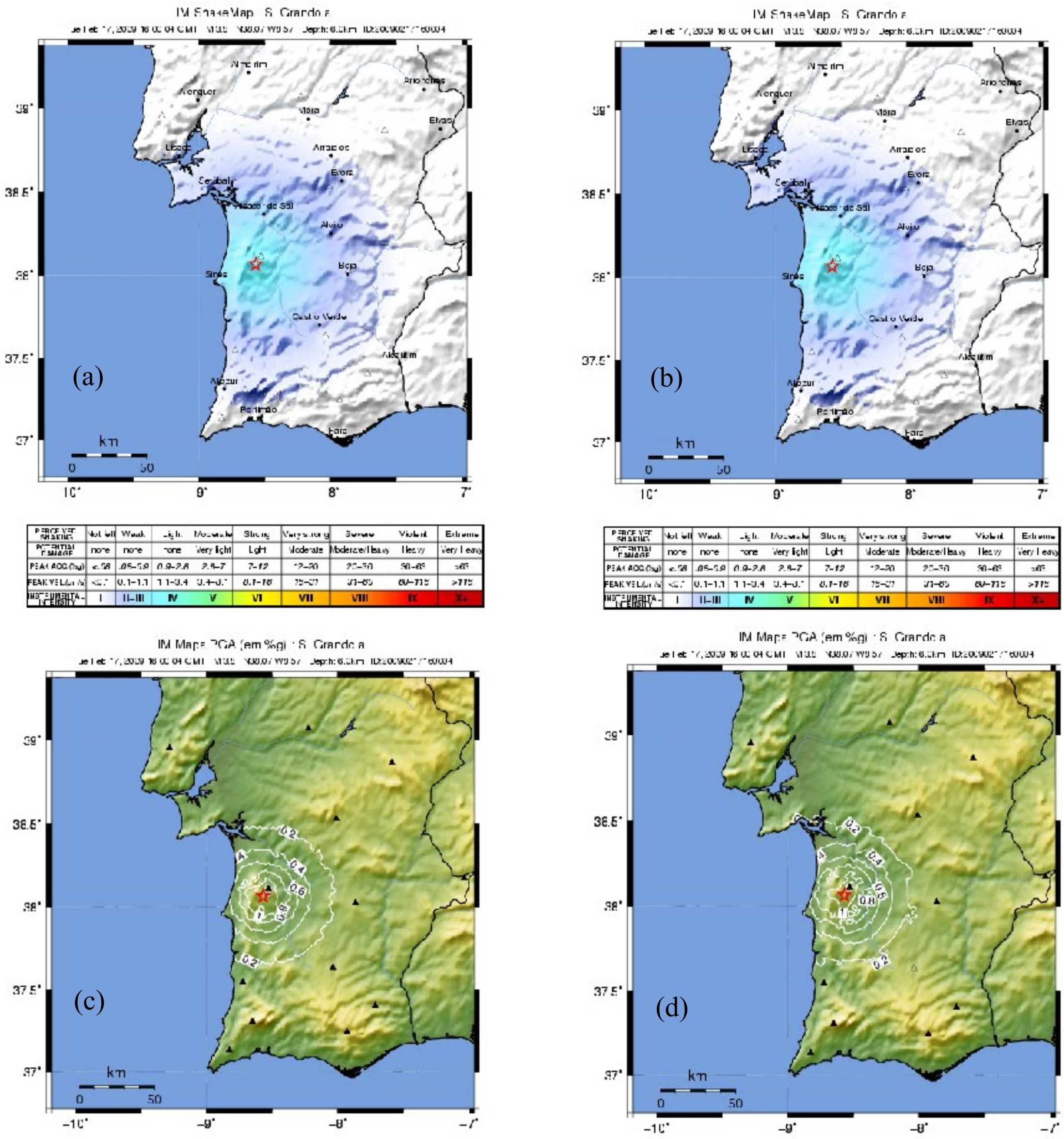

Figure 2.3. Shakemaps for 11 km S of Grândola earthquake (38,07ºN; 8,57ºW), on 2009-02-17, ML = 3,9. Site conditions derived from topography and geology, respectively: (a) and (b) instrumental intensity; (c) and (d) PGA. The epicentre is shown with a red star. The triangles shown the seismic stations.

2.3. Ground Motion Intensity Conversion Equations

Firstly, to generate the instrumental intensity maps we implemented the relations between Imm and peak ground motion proposed for California by Wald *et al.* (1999b), but the comparison with observed data indicates that this relations predict too low values for sites far from the epicentre. For Portugal mainland this relations underestimate the size of the macroseismic field. Then, we applied a new relation between Imm and PGA, that better fits the observed macroseismic intensities for Portugal mainland, derived from the relation proposed by Atkinson and Kaka (2007).

2.4. The Importance of Instrumental Data

The ShakeMap application to Portugal mainland relies primarily on observed shaking ground motion levels determined automatically from the stations of the Portuguese seismic network. In order to test the influence of the instrumental data on the maps generated by ShakeMap for a certain earthquake, were computed maps with and without instrumental measurements of PGA and PGV. The Figure 2.4. shows the instrumental intensity maps computed for the earthquake that occurred on 2010-03-27, located 6km NE of Sousel, with magnitude 4,1ML: (a) with instrumental measurements and (b) without instrumental measurements. Based on local felt reports, the maximum intensity determined was IV-V (Imm) at epicentre region (near Sousel). The macroseismic observations (independent from instrumental measurements) indicates that the macroseismic field constrained by observed ground motion is more realistic.

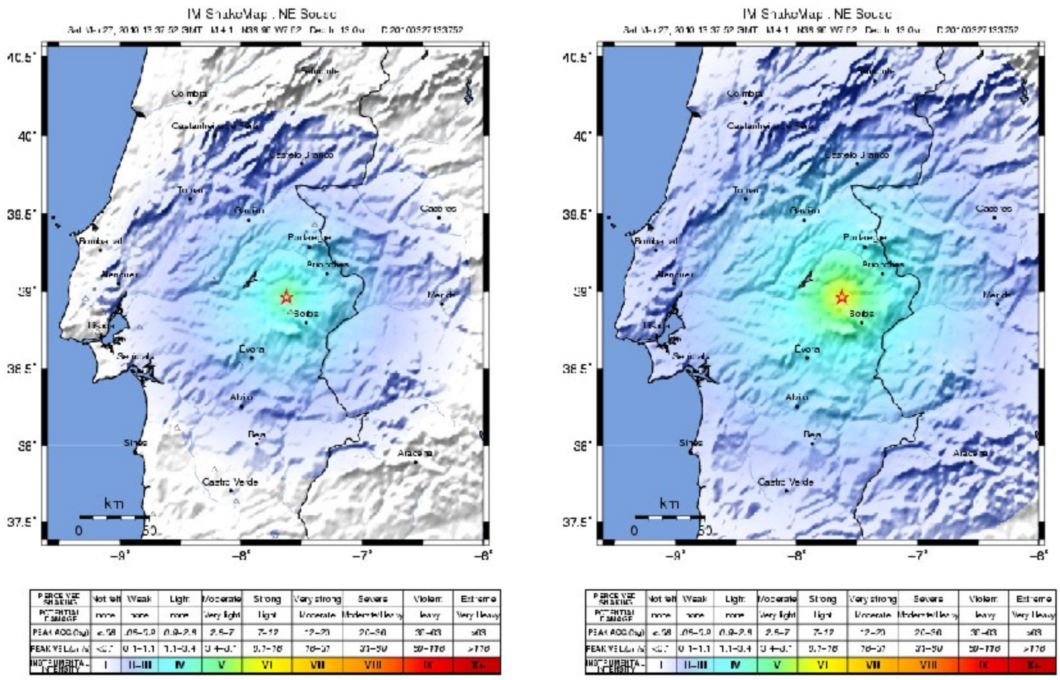

Figure 2.4. Instrumental intensity shakemap for the 6 km NE Sousel earthquake, on 2010-03-27, ML = 4,1: (a) with instrumental measurements; (b) without instrumental measurements. The epicentre is shown with a red star. The triangles shown the seismic stations.

3. APPLICATIONS OF SHAKEMAP TO PORTUGAL MAINLAND

Some results of the ShakeMap system application, with site conditions derived from geological information, to recent earthquakes that were felt at Portugal mainland are presented. The input data, obtained from the records of the Portuguese seismic network, are: (1) earthquake location and magnitude, and (2) PGA and PGV measured on the seismic stations records. Figure 3.1. shows the results obtained for the 12 km NNE of Silves earthquake, that occurred on 2011-03-26, with magnitude 4,0ML. Figure 3.1. (a) shows the instrumental intensity distribution estimated by ShakeMap. This map highlight the strongest shaking region (near Silves and Monchique) and the variation of perceiving shaking level. This result agrees with the values of intensity determined after earthquake occurrence. The earthquake was felt with intensity IV (Imm) in Monchique, Silves, Albufeira and Lagoa region, while in other sites of Algarve and Alentejo it was felt with lower intensities. The maximum extension of the macroseismic field agrees with the observations [Figure 3.2. (a)]. The contour map of Figure 3.1. (b) shows the PGA (%g) distribution on the topographic map. It shows the variation between 2,7 %g near the epicentre and 0,3 %g at the more distant contour.

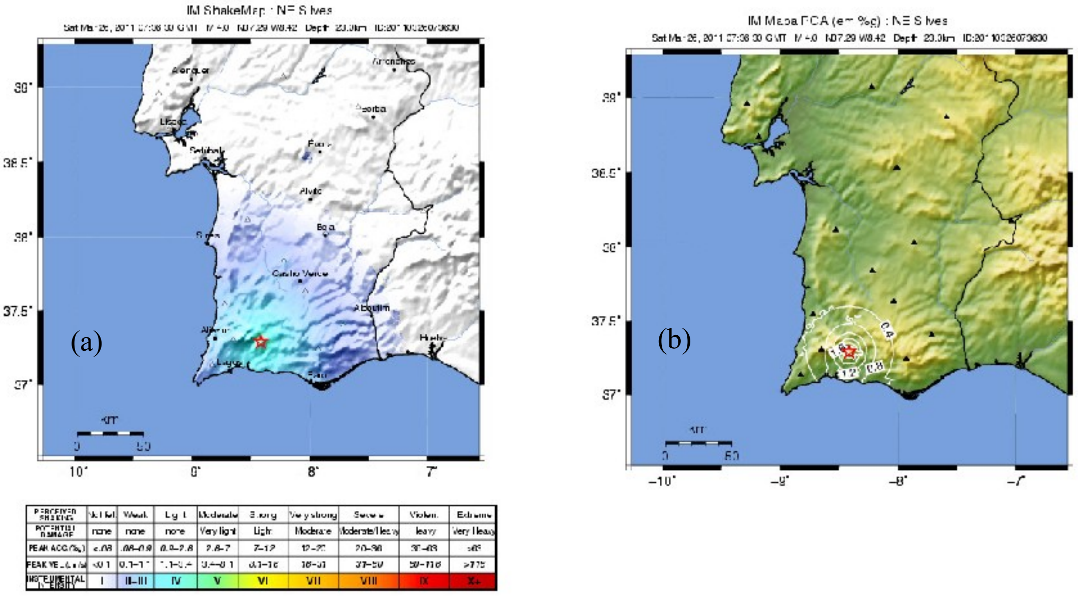

Figure 3.1. Shakemaps for 12 km NNE of Silves earthquake (37,29ºN; 8,42ºW), on 2011-03-26, ML = 4,0: (a) Instrumental Intensity; (b) PGA. The epicentre is shown with a red star. The triangles shown the seismic stations.

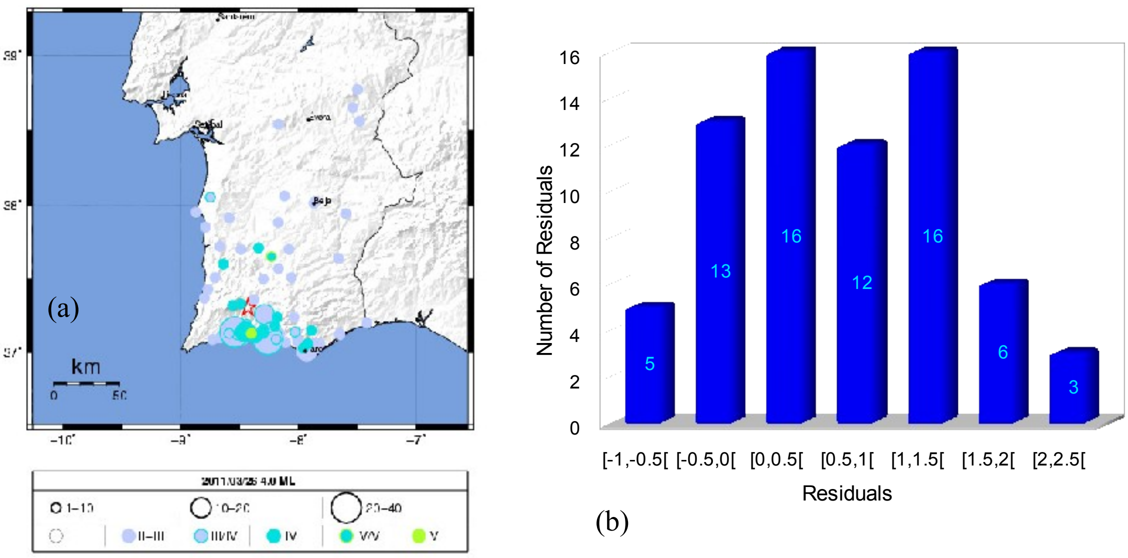

Figure 3.2. (a) Macroseismic observations for 12 km NNE of Silves earthquake, on 2011-03-26, ML = 4,0. The size of the open circles (first row) indicates the number of reports. The color of filled circles (second row) indicates the seismic intensity degree. The epicentre is shown with a red star. (b) Distribution of residuals (Macroseismic observations - ShakeMap intensity data).

The distribution of residuals [Figure 3.2. (b)] shows that the fit between instrumental ShakeMap intensities and macroseismic observations is generally good. In the case of this earthquake, from 71 residuals 46 have a less then one degree of difference.

4. FINAL REMARKS

The ShakeMap provides a rapid identification (< 3 min) of the strongest shaking region after an earthquake. The resulting maps are consistent with observed macroseismic intensity. However, we have some constraints in our examples, such as the reduced seismic stations coverage.

Implementation of ShakeMap in the IM seismic network is an ongoing project and we are working to improve the following aspects: 1) fully operational implementation of the new version (V3.5) of ShakeMap software; 2) inclusion of observed intensities as input data type (DYFI-IM); 3) attenuation and instrumental intensity relations.

REFERENCES

Atkinson, G.M., and Kaka, S. (2007). Relationships between Felt Intensity and Instrumental ground Motion in the Central United States and California, *Bulletin of the Seismological Society of America*, **97**, 497-510.

Borcherdt, R.D. (1994). Estimates of site-dependent response spectra for design (methodology and justification), *Earthquake Spectra*, **10**, 617-654.

Laboratório Nacional de Energia e Geologia (LNEG). (2010). Carta Geológica de Portugal à escala 1/1000.000.

Marreiros, C., and Carrilho, F. (2009). Geração de Mapas de Intensidade Instrumental - ShakeMap, *6º Simpósio de Meteorologia e Geofísica da APMG*, Caparica - Portugal, 60-64 (*in portuguese*).

Wald, D.J., and Allen, T.I. (2007). Topographic slope as a proxy for seismic site conditions and amplification: *Bulletin of the Seismological Society of America*, **97**, 1379-1395.

Wald, D.J., Worden, B.C., Quitoriano, V. and Pankow, K.L. (2005). ShakeMap Manual: Technical Manual, User's Guide, and Software Guide. *USGS Techniques and Methods*, **12-A1**, 1-156. http://pubs.usgs.gov/tm/2005/12A01/ [Website accessed on 2009].

Wald, D.J., Quitoriano, V., Heaton, T.H., Kanamori, H., Scrivner, C.W., and Worden, C.B. (1999). TriNet "ShakeMaps": Rapid Generation of Instrumental Ground Motion and Intensity Maps for Earthquakes in Southern California. *Earthquake Spectra.* **15,** 537-556.

Wald, D.J., Quitoriano, V., Heaton, T.H., and Kanamori H. (1999b). Relationships between peak ground acceleration, peak ground velocity and modified Mercalli Intensity in California. *Earthquake Spectr*a. **15***,* 557–564.

Wessel, P. and W. Smith, W. (2004). GMT version 4, Technical Reference and Cookbook.

Worden, C.B., Wald, D.J., Allen, T.I., Lin, K., Garcia, D., and Cua, G. (2010). A Revised Ground-Motion and Intensity Interpolation Scheme for ShakeMap, *Bulletin of the Seismological Society of America.* **100**, 3083-3096.