Mapping and cataloguing earthquake environmental effects for seismic hazard assessment: the contribute of remote sensing techniques

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Abstract - The traditional approach for seismic intensity assessment based mostly on effects on humans and manmade structures often results poorly constrained, especially in the epicentral area of strong-to-large earthquakes (intensity degree >IX) when damage to structures may be frequently afflicted by saturation, and in sparsely populated areas.
The application of the recent ESI intensity scale, which uses characteristics and distribution of earthquake environmental effects to evaluate seismic intensity, has confirmed that this approach provides more complete and reliable images of earthquakes, being environmental effects more closely related to the earthquake size.
Remote sensing techniques (multispectral images, hi-res DEMs from IFSAR and LIDAR data, InSAR images) play a crucial role in mapping earthquake environmental effects.
Therefore, seismic intensity assessments based on environmental effects are expected to strongly benefit from the regular application of remote sensing techniques to recent earthquakes and, in perspective, to the earthquakes that will occur in the next future.

Keywords: earthquake environmental effects, ESI intensity scale, seismic hazard.

1. INTRODUCTION

Seismic intensity assessments based only on the effects on humans and on damages to buildings and infrastructures are very effective for earthquakes occurred essentially in urbanized areas, but they are poorly constrained in sparsely populated zones. Moreover, the quite complete collapse of buildings generally associated to intensity X and above, causes also an upper limitation to the practical use of damage-based intensity scales for the highest degrees. Also, the time window of historical seismic catalogues is often much lower than the recurrence period of maximum expected earthquakes for the area.
These are strong limitations for seismic hazard assessments of many areas in the world. An attempt to overcome such limitations is the recent ESI 2007 intensity scale (Michetti et al., 2007), developed in the frame of INQUA, aimed at restoring and expanding the use of earthquake environmental effects (EEEs) for intensity assessment (e.g. Serva et al., 2007; Tatevossian, 2007; Lalinde and Sanchez, 2007) as it was the case in the earlier versions of the traditional intensity scales.
Another project supported by INQUA is now ongoing focused on the mapping and cataloguing of EEEs from seismic events worldwide. Such database will provide a further tool for improving seismic hazard assessment in many regions of the world.
This paper aims at showing that remote sensing analyses integrated with in situ data can play a significant role in mapping and characterizing numerous types of EEEs induced by recent seismic events, and for refining the intensity assessment, hence the dimension, of future moderate to strong earthquakes.

2. EARTHQUAKE ENVIRONMENTAL EFFECTS AND SEISMIC HAZARD: THE ESI 2007 INTENSITY SCALE AND THE EEE CATALOGUE

Earthquake Environmental Effects (EEEs) are any phenomena generated by a seismic event in the natural environment (Michetti et al., 2007). They can be categorized in two main types:

- Primary effects: the surface expression of the seismogenic tectonic source, including surface faulting, surface uplift and subsidence).
- Secondary effects: phenomena generally induced by the ground shaking. They are conveniently classified into eight main categories: slope movements, ground settlements, ground cracks, hydrological anomalies, anomalous waves (including tsunamis), other effects (tree shaking, dust clouds, jumping stones).

According to the original definition of seismic intensity, as developed at the beginning of the XX century (e.g. de Rossi, Mercalli, Cancani, Omori, Sieberg), the evaluation of the intensity of an earthquake has to be based on the effects on humans, on manmade structures and on natural environment. However, at that time the knowledge of effects produced by earthquakes on natural environment was poor. In the modern versions of the intensity scales (e.g. EMS 98, Grunthal, 1998) environmental effects were progressively less considered as diagnostic elements, their use was disregarded and the assessment was based only on the effects on humans and on damages to buildings. The application of modern scales to strong earthquakes has provided, especially in desert areas, intensity values far from being consistent with the earthquake energy. For example, the EMS maximum intensity value evaluated by Ambraseys & Bilham (2003) for the June 12, 1897, Assam earthquake in Pakistan (magnitude > 8) was based on the total collapse of very low-quality buildings which typically takes place already at intensity IX. Instead, the environmental effects, spread over an area of hundreds of thousands of km^2, offer a scenario much more consistent with the expected energy of the event.
Thus, with the target to make available a more effective tool for intensity assessment, a new intensity scale based only on the characteristics, size and distribution of environmental effects was devised (Michetti et al., 2007), named Environmental Seismic Intensity scale (ESI 2007). This scale is structured in 12 degrees, similarly to traditional intensity scales; it can be used alone or integrated with traditional scales, in case information on damages is also available.
Although the use of EEEs for intensity assessment is still controversial in the seismological community, ESI 2007 will unquestionably provide an added value to traditional intensity

evaluations, being applicable also in not inhabited areas and not afflicted by saturation of all diagnostic effects even for the greatest earthquakes. In addition, some environmental morphogenetic effects (either primary and secondary) can be stored in the palaeoseismological record, allowing to expand the time window for seismic hazard assessment up to tens of thousands of years (e.g. Guerrieri et al., 2007; Porfido et al., 2007).
Figure 1 is a graphic representation of the ESI 2007 intensity degrees: environmental effects can be used as diagnostic elements from the IV intensity degree and become progressively more diagnostic, especially from intensity IX when surface faulting is commonly observed.
In the frame of the INQUA (International Union for Quaternary Research) activities, a network of geologists, seismologists and engineers experts in the characterization of environmental effects from modern, historical and paleoseismic earthquakes is working on designing and compiling a new catalogue of Earthquake Environmental Effects (EEE Catalogue) of seismic events worldwide.
The catalogue will take advantage from the great amount of data on EEEs nowadays available, thanks to the strong development of palaeoseismological investigations and to the systematic revision of contemporary sources of historical earthquakes.
This catalogue is designed to collect environmental effects from recent, historical and palaeo earthquakes and it is structured in three different levels of detail (earthquake, locality, site). A geographic component of the catalogue has been developed in order to depict the spatial distribution of the recorded effects. The implementation of the catalogue is based on a volunteer collaboration of the participants to the project. Data are published in the catalogue after a validation of their compliance in order to ensure scientific and technical standards.

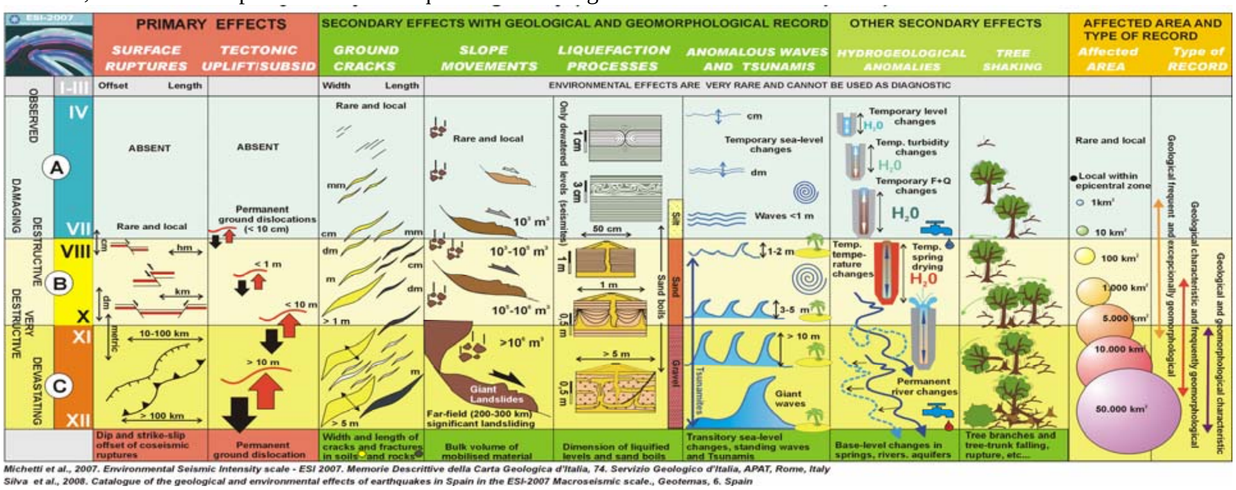

Fig. 1 – Graphic representation of the ESI intensity degrees for different types of environmental effects (Reicherter et al., 2009).

3. REMOTE SENSING TO MAP EARTHQUAKE ENVIRONMENTAL EFFECTS

Remote sensing techniques play a primary role in seismic hazard research. Since their appearance in the ’70s, optical (panchromatic, multispectral) and radar satellite images have contributed to recognize, map, and characterize active faults and folds, with a continuously growing role and reliability following the technological development, as proven by numerous structural, geological, and geomorphological studies (e.g., Tapponnier and Molnar, 1979; Trifonov, 1984; Ramasamy, 2005).
Concerning the mapping of earthquake environmental effects, the most effective use of remote sensing techniques is probably linked to the comparison of “pre and post earthquake” images. Evidently, repeated mapping before and after an earthquake would reveal the intervened ground modifications, with a detail basically depending on pixel size and length of time spans before and after image acquisitions.
Airborne and satellite optical imagery is commonly used in the immediate post-seismic phase in order to provide a detailed and reliable scenario of damages to the emergency management authorities (e.g. Yamazaki et al., 1998 for the1995 Hyogoken-Nanbu earthquake; Estrada et al., 2000 for the 1999 Izmit, Turkey earthquake). A similar approach can be extended for a detailed mapping of some types of environmental effects, which are also the major sources of hazard: typical examples are landslides, rock falls, ground ruptures, sinkholes, liquefaction. As well, satellite images provide a very efficient way to trace the spatial distribution of inundated areas by a collapsed dam or dyke or by a tsunami, and the consequent land modifications. See for reference the many satellite images of the December 26, 2004, Sumatra earthquake and following tsunami (e.g., www.globalsecurity.org/military/world/indonesia/tsunami-imagery.htm).
Furthermore, SAR Interferometry (InSAR) is a very promising technique for the characterization and mapping of EEEs. Differential InSAR (D-InSAR) data have been used since the early ’90s to evaluate the surface displacement due to moderate-to-strong earthquakes. For example, the well-known image of the Landers earthquake (M=7.3, 28 June 1992) was compiled on the basis of pre- and post-seismic scenes (Massonnet, et al., 1993) (e.g., Figg. 3a and 3b). Similar pictures were obtained for the M=7.2 Kobe, Japan, earthquake, 16/01/1995, Ozawa et al., 1997; Mw=6.0 Colfiorito, Italy, earthquake, 26/09/1997 (Salvi et al. 2000); M=6.8, 16/10/1999 Hector Mine Earthquake, USA (Pelzer et al., 2001); M=7.4, 17/08/1999 Izmit earthquake, Turkey (Stramondo et al., 2002).
Such examples have already demonstrated that multitemporal InSAR images can be conveniently used for mapping the spatial

distribution of coseismic surface faulting, as well as of other surface deformations linked to the seismogenic structure (e.g. tectonic uplift/subsidence), or associated to secondary shaking effects (e.g. landslides, ground settlements, etc..). The Permanent Scattered Interferometry (PS-InSAR) technique (Ferretti et al., 2001) can also provide valuable information (e.g., Bürgmann et al., 2006; Panagiotis et al., 2009), especially promising in the X band (e.g., the TerraSAR or Cosmo Skymed sensors), which allows to detect a much higher density of reflectors compared to present-day C band sensors. A potential limit of the PS technique is the need of a great number of images of the study area. Presently, the spatial and temporal coverage is satisfactory for the period of functioning of ERS satellites (1992-2001, with return periods of 35 days), much more episodic since then being not routinely carried out (as is the case for ENVISAT and RADARSAT). Such drawback will be hopefully overcome by a regular acquisition of images by more efficient satellites (e.g., Sentinel, Cosmo Skymed, etc..), which have return periods of 8-11 days and much better data storage capabilities, so that they should be programmed to regularly cover at least the regions most exposed to risk.

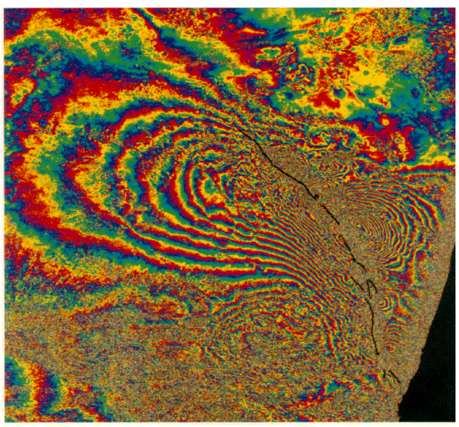

Figure 3 – "Historical" coseismic interferogram of Landers earthquake (from Massonnet et al., 1993). One fringe of colors represents 28 mm of change. Black lines show the surface rupture as mapped in the field.

IFSAR (Interferometric Synthetic Aperture Radar) and LIDAR (Light Detection and Ranging) are optical remote sensing technologies for high resolution DEM construction that, despite a few limitations (e.g., Damron and Carlton, 2000; http://earthdata.com/pdfs/FCT_Lidar-Educational_11-07.pdf), have rapidly gained popularity in geomorphology (e.g., Schultz, 2004), and, what is particularly interesting for the purposes of our project, in active tectonic studies (e.g., Harding and Berghoff, 2000; Kondo et al., 2008). In particular, the main advantages of the normally airborne LIDAR sensor, based on laser technology, are its elevated resolution and the capability of penetrating even in small openings in vegetated areas to show the ground morphology underneath (e.g., Figg. 4a-4b) with much higher detail than that offered by any other E.O. method (Harding and Berghoff, 2000; Nelson et al., 2003; Cunningham et al., 2006). Clearly, while pre- and post-event satellite IFSAR DEMs are more feasible, being based on the same radar images cited before, it is to date highly improbable to have on hand a pre-earthquake LIDAR DEM.

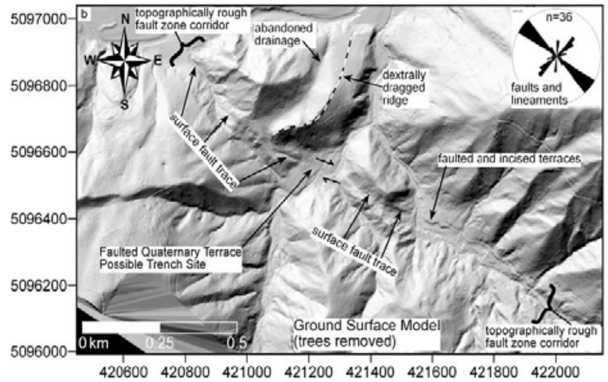

Figure 4 – LIDAR image of the Idrjia Fault in Slovenia (from Cunningham et al. 2006).

4. CONCLUSIONS

Already nowadays (likely with significant improvements in the next future), satellite and airborne multispectral images, hi-res DEMs constructed from IFSAR and LIDAR data, D-InSAR and PS-InSAR data provide efficient tools to map in a very quick and systematic mode and at an appropriate level of resolution many land features. Especially when suitably joined together, the radar and laser sensors, which are able to map the ground shape and its temporal changes with great precision and over large areas, the hi-res multispectral sensors and in-situ data (where available) appear able to provide the most effective way to identify the morphogenetic effects of earthquakes. In fact, the latter, particularly surface faulting, ground cracks, landsliding, uplift and subsidence (i.e., the most relevant for hazard and risk assessment), cannot be often easily recognized in the field systematically, particularly in poorly accessible areas. This is true either for the assessment of the most affected region (which allows a more appropriate and documented evaluation of size of earthquake) and for the recognition of residual/future risk in the emergency and post-event stages.

Therefore, researches in the field of seismic intensity assessment based on environmental effects are expected to strongly benefit from the regular application of remote sensing techniques to recent earthquakes and, in perspective, to the earthquakes that will occur in the next future.

Of course, the use of remote sensing techniques for the EEEs characterization and mapping requires to develop a standard methodology based on case studies which integrate remote sensing and in situ data. Such approach should be developed by a joint effort between researchers dealing with EEEs and the community of experts in remote sensing.

A first step in this direction will be the contribution of the EEE Catalogue to the GEO (Group on Earth Observations, www.earthobservations.org) initiative, with particular regard to the SBA "Disasters" (Task DI-09-01: Systematic Monitoring for Geohazards Risk Assessment). In this frame, the EEE catalogue will provide the necessary in situ data for integrating and validating assessments based on remote sensing analyses.

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