Open source GIS Tools to Map Earthquake Damage Scenarios and to Support Emergency

Maurizio Pollino, Antonio Bruno Della Rocca, Grazia Fattoruso, Luigi La Porta, Sergio Lo Curzio, Agnese Arolchi
ENEA - National Agency for New Technologies, Energy and Sustainable Economic Development
Casaccia Research Centre – Rome, Italy
Portici Research Centre - Portici (Naples), Italy
{maurizio.pollino, grazia.fattoruso, dellarocca, laporta, sergio.locurzio, agnese.arolchi}@enea.it

Valentina James, Carmine Pascale
Consorzio T.R.E. - Tecnologie per il Recupero Edilizio
Naples, Italy
{valentina.james, carmine.pascale}@consorziotre.it

***Abstract*—The latest improvements in geo-informatics offer new opportunities in a wide range of territorial and environmental applications. In this general framework, a relevant issue is represented by earthquake early warning and emergency management. In the recent years, the scientific community has recognized the added value of a geo-analytic approach in order to support complex decision making processes for critical situations, due to disastrous natural events like earthquakes. This paper describes the research activities concerning a GIS-based solution, which is aimed at the development of seismic Early Warning Systems (EWSs). In this context, an innovative open source GIS has been studied, implemented and integrated as component of the seismic EWS. Its architecture consists in: a geospatial database system; a local GIS application for analyzing and modelling the seismic event and its impacts and supporting post-event emergency management; a WEB-GIS module for sharing the geo-information among the public and private stakeholders and emergency managers involved in disaster impact assessment and response management.**

Keywords-GIS, Open Source, Spatial analysis, Early Warning Systems, Emergency Management

I. INTRODUCTION

Over the last 100 years, more than 1,100 disastrous earthquakes have occurred worldwide, causing more than 1,500,000 casualties: buildings collapsing is about 90% of direct deceases [1]. Those occurrences are clearly linked to world's population increase jointly with cities expansion. In particular, the urban growth process is often characterized by lack of planning and unsuitable land use: those factors contribute to dramatically amplify the damages due to seismic events. In this framework, Geographical Information (GI) technologies can play a fundamental role both in seismic risk assessment and in complex decision making in the course of critical situations [2], supporting natural disaster early warning and emergency management tasks. The need for related standard and effective spatial GUI (Graphical User Interface), geo-visual analytic tools, integrated geographic platforms (GIS), spatial data infrastructures has been outlined within several research works (see [3], [4], [5], [6], [7] and [8] among others).

As regards the early warning and emergency response issues related to seismic events, the recent advances in geo-informatics, in communication and sensor technologies have opened new opportunities. The up-to-date earthquake Early Warning Systems (EWSs) consist in seismic sensor networks connected to a central unit (operating centre, OC) by high-speed communication network. The kernel of the operating centre is a decision support system (DSS) that should enable the operators to make decisions and to disseminate EW. The generated alarm should be used to evacuate buildings, shut-down critical systems (e.g., nuclear and chemical reactors), put vulnerable machines and industrial robots into a safe position, stop high-speed trains, activate structural control systems and so on. Immediately following an earthquake, the operating centre should also support emergency response and rescue operations.

Until recently, the most common information available immediately following a significant earthquake is its magnitude and epicentre. However, the damage pattern is not a simple function of these two parameters alone, and more detailed information must be provided for properly ascertain the situation and adequately plan and coordinate emergency response. Just as an example, although an earthquake has one magnitude and one epicentre, it produces a range of ground shaking levels at sites throughout the region depending on distance from the earthquake, the rock and soil conditions at sites and variations in the propagation of seismic waves. Hence, GIS systems can support quick analysis of the situation immediately following an earthquake and facilitate critical decision making processes. Prototype systems, currently available in literature, have been on purpose developed ([6],

[7] and [9]) and are fundamentally based on commercial technologies [6] and [9].

In Paragraph II of this paper it is described the innovative free/open source GIS system [10] developed as integrated component of a seismic EWS. In particular, Par. II.B describes its architecture, consisting in a geospatial database system, a local GIS application for analysing and modelling the seismic event and its impacts, a WebGIS module for sharing the geo-information (listed in Par. II.C) and supporting post-event emergency management. Paragraph III is devoted to describe and discuss the results, in terms of expected seismic damage in structures and infrastructures, and the tools to support a rapid impact assessment and the disaster response. Finally, conclusions and future developments are reported in Par. IV.

II. Materials and Methods

A. *Case of study and context*

The research work here described is focused on the development of a methodology for a regional seismic risk analysis by using GIS technologies and methodologies. The study is part of a seismic hazard, vulnerability and risk analysis for the seismically active areas in the Campania Region (Southern Italy) (Fig. 1).

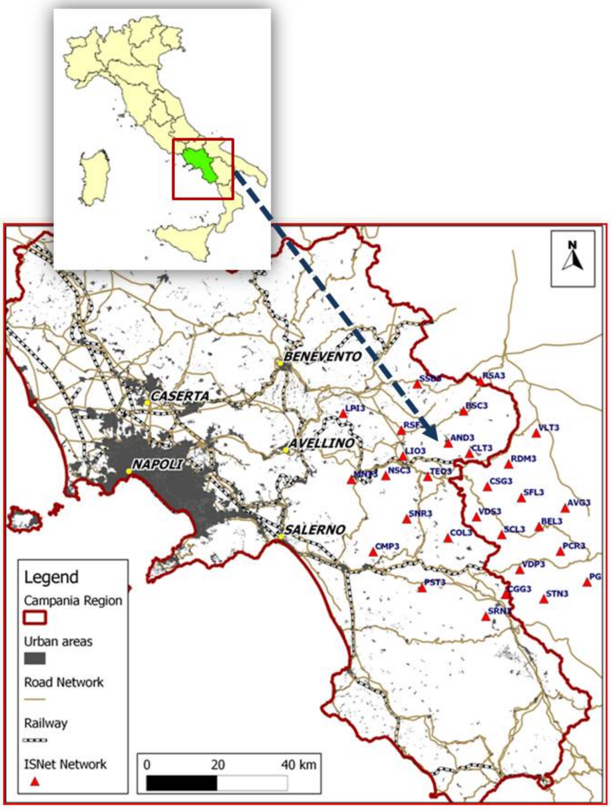


Figure 1. Geographic location of the study area

The main goal is to develop an integrated system for emergencies management in case of natural disasters, focusing on risk assessment and mitigation, early warning (EW) methodologies and post-event support activities. Further, the System is based on data coming from an existing seismic network located within the study area (ISNet, Irpinia Seismic Network [11]). The entire system improves a hybrid EWS based on a regional approach that assumes that a dense seismic network is deployed around the fault zone and a site specific approach, which aims to the protection of specific facilities.

The earthquake EWS is based on the different propagation speeds between seismic waves and signal transmission, since the alert is given only after the detection of phenomena indicating the generation of a possibly dangerous event and it has to reach the terminal before it starts damaging a given location this allows an alert time of that goes for seconds to tens of seconds.

The functions of a Seismic Alert Management System is related to two different phases of an event:

- Early Warning: 10-20 seconds after the main shock the system should predict the ground motion intensity, evaluate the epicentre and provide dissemination of information;
- Post event warning: 100-200 seconds after the main shock, the decision support system should address a preliminary scenario based on spatial interpolation of ground motion and then a detailed scenario, based on simulation of simplified source/propagation models.

The OC receives and elaborates information coming from monitoring systems (ISNet) and allows to activate a series of automatic security measures for sensible structures and infrastructures (e.g., high-speed railways, gas and electrical plants and installations, hospitals, strategic buildings, etc). The OC also coordinates the rescue operations in the immediate post-event phase. Moreover, the System has been designed not only to manage the emergency tasks, but also to provide a real-time monitoring of the vulnerability of structures and infrastructures within the area of interest.

The OC is supported by a GIS system that represents and performs the geographical information related to the event source (real-time and near real-time phases) and analyses in few minutes the expected damages on structures and buildings.

B. *GIS System architecture*

The geospatial analysis and visualization play a fundamental role in earthquake EW and post-event emergency management: to this purpose, the GIS has been integrated into the overall Project architecture as geographic interface of the OC. Consequently, basic information and thematic maps are stored and managed into a geospatial database purposely implemented, so that it is possible to display and query the data by means a map viewer. Fig. 2 shows the GIS logical architecture, developed by using free

 ISBN: 978-1-61208-178-6

open source software (FOSS). It consists in the following modules (between brackets the FOSS used):

1. *Geodatabase Module* (PostgreSQL/PostGIS);
2. *GIS Module* (Quantum GIS);
3. *WEB-GIS Module* (MapServer).

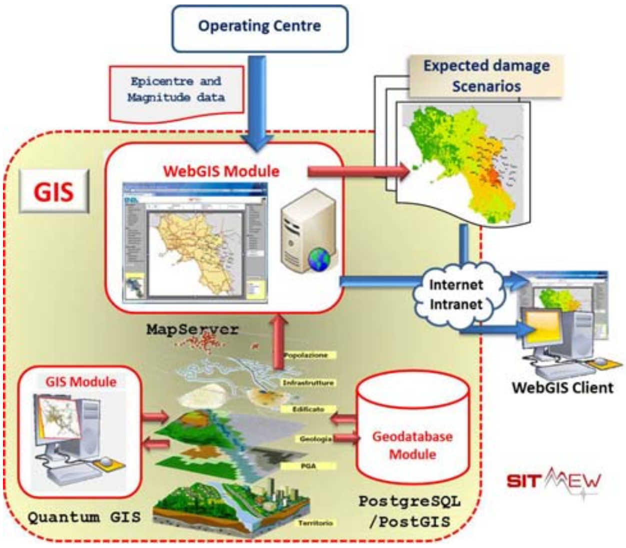


Figure 2. GIS architecture schema

Geodatabase Module has been designed to manage and integrate geospatial data provided as input to the system, including the alphanumeric data related to seismic events (e.g., magnitude and epicentre, recorded and processed by the OC) and specific geospatial data related to the area of interest (geology, vulnerability maps, urbanized areas, Census, etc.). The FOSS technologies chosen to implement this module was PostgreSQL/PostGIS (www.postgresql.org and http://postgis.refractions.net/).

The *GIS Module*, in direct connection with *Geodatabase Module*, is devoted to process geographical data and spatial information. By means of spatial analysis procedures and geo-processing operations, this module provides a complete and up-to-date description of the study area and, as final result, the maps of expected damage. After a comparative analysis between the main FOSS desktop GIS platforms available [10], the one chosen to implement the *GIS Module* was QuantumGIS (http://www.qgis.org/). The comparison was based on main functionalities, technology, geo-processing capabilities and interoperability with the other FOSS packages used for the modules *Geodatabase* and *WEB-GIS*.

Finally, the *WEB-GIS Module* was implemented by using the FOSS Mapserver (http://mapserver.org/): it allows the consultation of geo-spatial data stored in the system and support the management of activities during the immediate seismic post-event phase.

The main features of the GIS subsystem can be summarized in:

- Description and characterization of the study area;
- Production of thematic maps (e.g., expected damage scenarios) to support the management of near-EW and post-event phases;
- Consultation via intranet/internet to data and maps.

C. *Materials*

The *Geodatabase Module* has been purposely implemented to provide the spatial description of the study area of the Campania region (Fig. 1) and structured into different logical schemes (homogeneous for geographic data type). In detail, the following data (UTM-WGS84 reference system) have been used:

- Basic GIS Layers (Administrative boundaries, road network, railways, hydrograph, etc ...);
- Thematic Maps (hydrology, geomorphology, seismic classification, etc.);
- 1:25.000 Cartography;
- Census data;
- Digital Terrain Model (DTM, 20 m ground spacing);
- Geographic location and data of ISNet sensors;
- PGA (Peak Ground Acceleration) distribution maps;
- Data from parametric catalogue of damaging earthquakes in Italy (INGV, Italian National Institute of Geophysics and Volcanology).

Those layers and information have represented the basis of the spatial analysis carried out through the *GIS Module* and, along with the new maps produced, have been stored and managed into the *Geodatabase Module*.

D. *Spatial analysis*

As stated before, magnitude and epicentre are fundamental information available immediately after a significant earthquake. Considering other parameters such as rock and soil conditions, distance from the epicentre and variations in the propagation of seismic waves, it is possible to produce the ground shaking maps by means of spatial analysis and geo-processing tools. Then, such maps can be overlaid with inventories of buildings, critical facilities, transportation networks and vulnerable structures and provide a mean of prioritizing response.

The work here presented is based on several of these concepts in a simplified analysis over a fairly large region and exploits data from the parametric catalogue of damaging earthquakes in the Italian area, achieved by INGV [12]. The GIS system has been opportunely designed to process and achieve shake maps and multiple scenarios with different local magnitude (ML) for different epicentres. Considering the spatial data stored into the *Geodatabase* module and the geographic location of the ISNet sensors, the system has been structured to receive earthquake from the OC (epicentre and ML) in order to return PGA maps, vulnerability maps and expected damage scenarios. In this way, it is possible to have a preliminary assessment of the expected damages after a seismic event of given magnitude and epicentre. The model developed within the GIS systems takes into account the potential effects of the earthquake on manmade objects and population: for this reason, the vulnerability has been expressed in terms of macroseismic intensity I_{MCS}. In particular, PGA and I_{MCS} values have been correlated using the law proposed by Sabetta and Pugliese [13] to calculate the PGA distribution and to correlate the PGA to I_{MCS} [14]. In order to estimate the surface ground shaking in the region, the following attenuation relationship [13] has been used (1):

$$\log_{10}(Y) = a + bM + c\log_{10}(R^2 + h^2)^{1/2} + e_1S_1 + e_2S_s \pm \sigma \quad (1)$$

being Y the parameter to evaluate the PGA for this case study, M the magnitude (local), R the distance (from the epicentre) and σ the standard deviation of log Y. The parameters S_1 and S_2 refer to site classification and take the value of 1 for shallow and deep alluvium sites, and zero otherwise. The analysis don't take in account of site effects and the PGA has been calculated considering bed rock condition. To convert IMCS to PGA, the following equation (2) has been used:

$$\log PGA = 0.594 + 0{,}197 \cdot I_{MCS} \quad (2)$$

III. Results

A. Vulnerabilty Index

To evaluate the vulnerability is required a suitable inventory of the buildings in the region and well-defined relationship between earthquake motion (including local site effects) and both structural and non-structural damage. The estimation of buildings vulnerability is fundamental to provide a measure of their susceptibility to be damaged in consequence of specified seismic events. To obtain this information, as basic source has been used the inventory of the buildings extracted from ISTAT [15] Census data (2001). Those data, in table format, have been linked to the respective census section (in vector format) and processed using spatial analysis GIS functions. In this way, it has been possible to produce new GIS layers containing aggregated information about built-up density, structural typology (2 classes: Masonry or Reinforced Concrete), age of construction (7 classes), number of storeys (4 classes). Adapting the approach proposed by Giovinazzi and Lagomarsino [16] and using the above described data, thus, it has been calculated the vulnerability index I_v for each census section [17]. Firstly, the buildings have been basically distinct (Table I) in Masonry (M) or Reinforced Concrete (RC). Other information contained in the ISTAT data (number of floors and period of construction) have been instead used to correct the vulnerability index for each category and considered as behaviour modifiers (Table II).

TABLE I. Vulnerability indices for building typologies and construction age over the study area

	Construction age	I_V	
		Masonry	**RC**
1	Before 1919	50	-
2	1919 ÷ 1945	40	-
3	1946 ÷1961	30	20
4	1962 ÷1971	30	20
5	1972 ÷1981	20	20
6	1982 ÷1991	20	0
7	After 1991	20	0

TABLE II. Vulnerability index modifiers depending of number of storeys and construction age

Age / **N. of storeys**	*<1919*	*1919-1945*	*1946-1961*	*1962-1971*	*1972-1981*	*1982-1991*	*>1991*
1	0	0	0	0	0	-6	-6
2	+5	+5	+5	+5	+5	0	0
3	+5	+5	+5	+5	+5	0	0
>4	+10	+10	+10	+10	+10	+6	+6

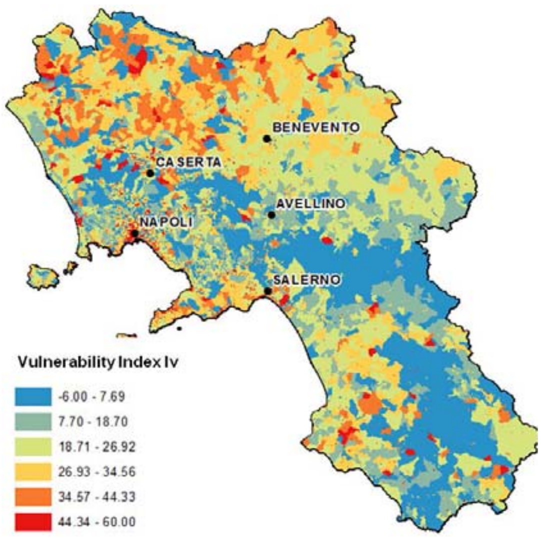


Figure 3. Map of the vulnerability index I_V: values for Census sections

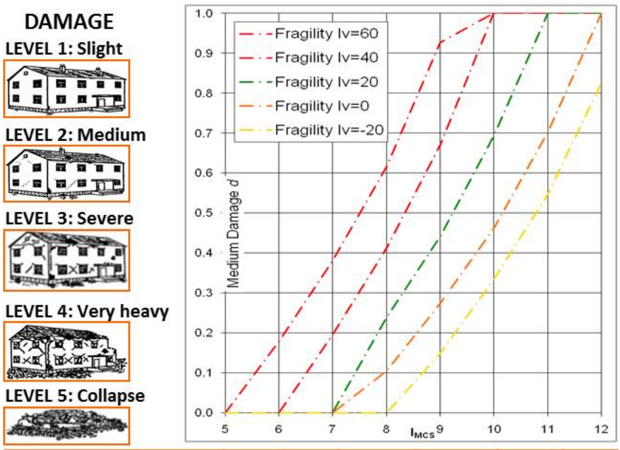
Those modifiers are used to increase or decrease in the I_v index, depending on the characteristics of the buildings within the area considered. Because each building has his intrinsic vulnerability and census sections may contain buildings with different values of the index, I_V (ranging from -6 to 60) has been calculated for each polygon as a weighted average of the values due to different building characteristics (Fig. 3).

B. Maps of expected damage

Despite the obvious approximations, the preliminary assessment of seismic vulnerability performed by the above described approach has the advantage of an extensive and prompt application, especially considering a large area like the Campania Region. After converting each map into an array of numeric values with square cell size 50 m spatial resolution, consistent with other data, it has been possible to process (by means spatial analysis modelling) the thematic maps representing PGA, I_{MCS} and I_V in overlay with the spatial representation of Census data above described. According to Giovinazzi and Lagomarsino [16], the damage d has been calculated (3) as:

$$d = 0.5 + 0.45\{\arctan[0.55(I_{MCS} - 10.2 + 0.05 \cdot I_V)]\} \quad [3]$$

The formula (3) expresses the relationships between I_{MCS} and damage d, according to the trend of fragility curves depicted in Fig. 4.



Levels of Damage	0	1	2	3	4	5
Factor of Damage (f_d)	0	0.01	0.1	0.35	0.75	1

Figure 4. Fragility curves and Vulneravility Index I_V relationships, in terms of mean damage

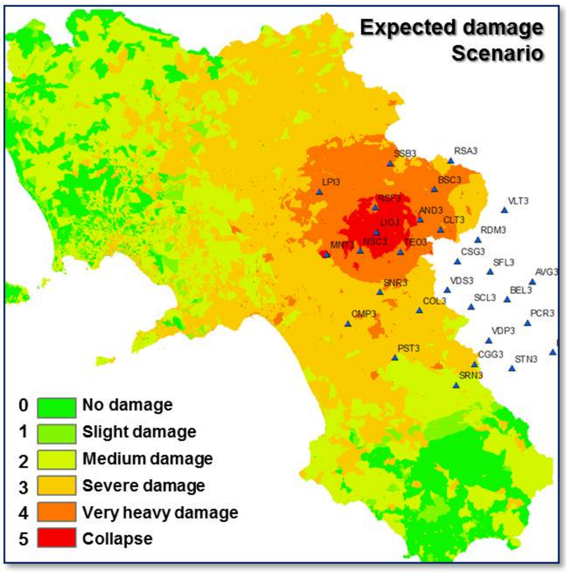


Figure 5. Scenario: example of map of expected damage (categorized according to different levels of damage)

Therefore, from a qualitative point of view, it is possible to establish a relation between I_{MCS} and d by differentiating the mean damage into 5 different levels (Fig. 4, left side). Then, the damage can be expressed by an a-dimensional parameter f_d (ranging between 0 and 1), in order to obtain a correspondence (Fig. 4, underside) between the levels of damage and the values of d calculated by means the formula (3). Using this approach, have been obtained the expected damage maps (Fig. 5) for each seismic event simulated: the variables are represented by epicentre coordinates and local magnitude ML.

C. *The WebGIS*

The primary goal of the *WEB-GIS Module* is to make geographic data and thematic maps available to specific end-users and, potentially, to the public. The application allows the end-user to view spatial data within a web browser, without a specific GIS Desktop software. This Module provides interactive query capabilities and integrates the GIS solutions with other technologies, according to server-side or client-side applications. Over 30 different WebGIS packages are available at present. Among these, the most popular and commercially successful are ESRI ArcIMS (www.esri.com/arcims), Intergraph GeoMedia WebMap (www.intergraph.com) and AutoDesk MapGuide (www.autodesk.com).

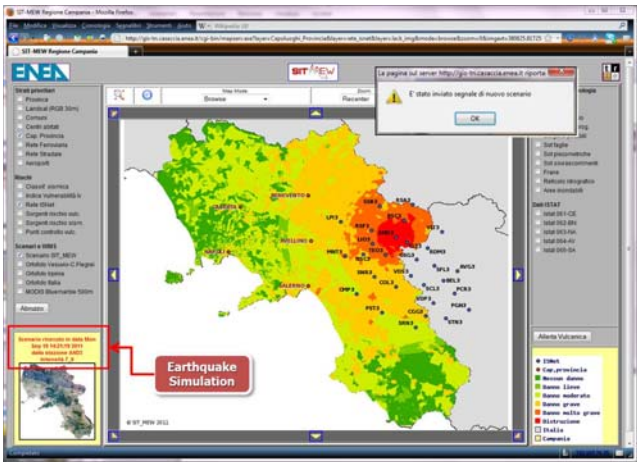


Figure 6. WebGIS visualization of damage scenario (Earthquake simulation: epicentre in Andretta, ML 7.0)

UNM MapServer is a FOSS application developed by the University of Minnesota through a NASA sponsored project, that has been widely adopted. The package is a free alternative to other commercial applications and it is a good solution when highly customised applications are needed. MapServer is a Common Gateway Interface (CGI) programme that sits inactive on the web server. MapServer provides a scripting interface for the construction of web and stand-alone applications, adding WebGIS capability to popular scripting languages. The expected damage scenarios produced through the spatial analysis function above described are the main features of the *WEB-GIS Module* (Fig. 6). The Module allows to display these maps in overlay and in relationship to each other data stored into the *Geodabase Module*: basic geographic layers, geology, shaking maps, urban areas, Census data, PGA and I_V maps, Scenarios, etc.

IV. CONCLUSIONS AND FUTURE DEVELOPMENT

A procedure for mapping and assessing buildings seismic vulnerability has been developed integrating spatial analysis and using geoprocessing tools [18]. The GIS approach, including the reclassification and overlay of each spatial data layer, has been applied to analyse the potential hazard that would result from a certain magnitude earthquake. In this way, it has been possible to define a conceptual model that, exploiting the GIS architecture here described, allows a quick management of damage scenarios. Maps of PGA, I_{MCS}, I_V and building characteristics reported in the Census data represent fundamental parameters to detect the areas (subdivided in parcels) that could probably face serious problems in consequence of total or partial collapses.

Further, the model described in this paper is fully functional and available to regional scale and the advantage of GIS methodologies is that the system is open and additional data can be integrated as soon as new information is available. In perspective, multi-source data and GIS integrated analysis can contribute to a better emergency planning, providing fundamental information for immediate response when future disasters will occur. A interactive DSS based on GIS approach could support the public government to address, in the near post-event phase, activities related to emergency management and damage evaluations for buildings and lifelines. Finally, the global architecture of the system will be enhanced also taking into account the implementation of a backup system, in order to manage and/or mitigate the effects potentially coming from a network failure (electricity, telecommunications, etc.).

ACKNOWLEDGMENT

The methodologies here described have been designed and developed within the context of “SIT_MEW” Project (*Sistema integrato di telecomunicazioni a larga banda per la gestione del territorio e delle emergenze in caso di calamità naturali comprensivo di Metodologie di Early Warning*), which is a R&D project co-funded by Italian Ministry of Education, Universities and Research (MIUR) in the framework of the “Grandi Progetti Strategici” (GPS) national program.

REFERENCES

[1] Lantada, N., Pujades, L. G., and Barbat, A. H., “Vulnerability index and capacity spectrum based methods for urban seismic risk evaluation” Nat. Hazards, 51, 2009, pp. 501-524

[2] Cova, T. J., “GIS in emergency management”. In: Longley, P. A. et al. (eds). Geographical Information Systems, V 2: Management Issues and Applications, John Wiley & Sons Inc., New York, 1999, pp. 845-858

[3] Andrienko, N. and Andrienko, G., “Intelligent Visualization and Information Presenattion for Civil Crisis Management” Transaction in GIS, 11 (6):, 2007, pp. 889-909

[4] Charvat, K., Kubicek, P., and Talhofer, V., Konecny M., Jezek, J., “Spatial Data Infrastructure and geo-visualization”, In: Emergency management. Resilience of Cities to Terrorist and other Threats, Springer Science, 2008, pp. 443- 473

[5] ESRI White Paper: Geographic Information Systems Providing the Platform for Comprehensive Emergency Management, 2008

[6] FEMA 2008. HAZUS-MH Estimated Annualized Earthquake Losses for the United States (FEMA 366). Federal Emergency Management Agency, Washington, DC, April 200.

[7] Mueller, M., Dransch, D., and Wnuk, M., “Spatial GUIs for Complex Decision Support in Time-critical Situations” In: XXIII International Cartographic Conference, 4-10 August 2007, Moscow Russia, 2007

[8] Della Rocca, A.B, Fattoruso, G., Locurzio, S., Pasanisi, F., Pica, R., Peloso, A., Pollino, M., Tebano, C., Trocciola, A., De Chiara, D., and Tortora, G., “SISI Project: Developing GIS-Based Tools for Vulnerability Assessment” In: Sebillo, M., Vitiello, G., Schaferer. G. (eds) LNCD, Vol. 5188, Springer, Heidelberg, 2008, pp. 327-330, doi:10.1007/978-3-540-85891-1_37

[9] Theodoridis, Y., “Seismo-Surfer: A Prototype for Collecting, Querying, and Mining Seismic Data” In: Y. Manolopoulos et al. (eds.) PCI 2001. LNCS, vol. 2563,. Springer Berlin-Heidelberg, 2003, pp. 159--171

[10] Steiniger, S. and Bocher, E., “An overview on current free and open source desktop GIS developments” Int. J. Geogr. Inf. Sci., 23: 10, 2009, pp. 1345-1370

[11] Irpinia Sesimic Networ (ISNet). http://isnet.amracenter.com/ <retrieved: Nov., 2011>

[12] INGV, Italian National Institute of Geophysics and Volcanology. http://www.ingv.it/eng/ <retrieved: Nov., 2011>

[13] Sabetta F., and Pugliese A., “Estimation of response Spectra and Simulation of Non-Stationary Earthquake Ground Motion”. Bulletin of Seismology Society of America, Vol. 86 - No 2, April 1996, pp. 337-352

[14] Decanini, L., Gavarini, C., and Mollaioli, F., “Proposta di definizione delle relazioni tra intensità macrosismica e parametri del moto del suolo” In: Atti 7° Convegno Nazionale “L’ingegneria sismica in Italia”, Siena, vol. 1, 1995, pp. 63-72

[15] ISTAT, Italian National Institute of Statistics. http://www.istat.it/en/ <retrieved: Nov., 2011>

[16] Giovinazzi, S., and Lagomarsino, S., “Una metodologia per l’analisi di vulnerabilità sismica del costruito” In: Atti X Congresso nazionale “L’ingegneria sismica in Italia”, Potenza – Matera, 2001

[17] Borfecchia, F., De Cecco, L., Pollino, M., La Porta, L., Lugari, A., Martin, S., Ristoratore, E., and Pascale, C., “Active and passive remote sensing for supporting the evaluation of the urban seismic vulnerability” Italian Journal of Remote Sensing, 42(3), 2010, pp. 129-141, doi: 10.5721/ItJRS201042310

[18] Pollino, M., Fattoruso, G., Della Rocca, A. B., La Porta, L., Lo Curzio, S., Arolchi, A., James, V. and Pascale, C.: An Open Source GIS System for Earthquake Early Warning and Post-Event Emergency Management. In: B. Murgante, O. Gervasi, A. Iglesias, D. Taniar and B. O. Apduha (eds.) LNCS, vol. 6783, Springer Berlin-Heidelberg, 2011, pp. 376-391, doi: 10.1007/978-3-642-21887-3_30

[19] UNM MapServer. http://mapserver.org/ <retrieved: Nov., 2011>