Improving emergency preparedness with simulation of cascading events scenarios

Alexander Garcia-Aristizabal
Center for the Analysis and Monitoring of Environmental Risk (AMRA), Naples, Italy
alexander.garcia@amracenter.com

Maria Polese
Department of Structures for Engineering and Architecture, University of Naples Federico II
maria.polese@unina.it

Giulio Zuccaro
Department of Structures for Engineering and Architecture, University of Naples Federico II
zuccaro@unina.it

Miguel Almeida
Centre for Forest Fire Research ADAI, Coimbra, Portugal
miguellmd@yahoo.com

Christoph Aubrecht
AIT Austrian Institute of Technology GmbH, Vienna
Christoph.Aubrecht@ait.ac.at

ABSTRACT

Natural or man-made disasters can trigger other negative events leading to tremendous increase of fatalities and damages. In case of Low Probability - High consequences events, decision makers are faced with very difficult choices and the availability of a tool to support emergency decisions would be very much beneficial. Within EU CRISMA project a concept model and tool for evaluating cascading effects into scenario-based analyses was implemented. This paper describes the main concepts of the model and demonstrates its application with reference to two earthquake-triggered CE scenarios, including (the first) the falling of an electric cable, ignition and spreading of forest fire and (the second) the happening of a second earthquake in a sequence. Time dependent seismic vulnerability of buildings and population exposure are also considered for updating impact estimation during an earthquake crisis.

Keywords

Cascading effects, impact scenarios, event tree, time-dependent vulnerability, forest fire.

INTRODUCTION

The cascading effects result as a consequence of interactions generated by cause/effect relationships among different phenomena. The nature of these interactions may be described by a wide set of phenomenological relationships, and it makes difficult to set a generalized procedure for the quantification of cascading effects. For this reason and to simplify the setting of the problem for quantitative purposes, a generic taxonomy of the possible kinds of interactions can be defined. Following the framework presented in Marzocchi et al. (2012) and Garcia-Aristizabal et al. (forthcoming-2015), it is possible to define a generalized taxonomy of interactions considering two possible kinds of interactions, namely, (1) interactions at the hazard level, in which the occurrence of a given initial triggering event entails a modification of the probability of occurrence of a secondary event and (2) interaction at the vulnerability (or damage) level, in which the main interest is to assess the effects that the occurrence of one event (the first one occurring in time) may have on the response of the exposed elements against another event (that may be of the same kind as the former but also a different kind of hazard). A combination of both kinds of interactions is another possible case.

From the seismic risk assessment point of view, the cascades of events occurring after an earthquake may represent an important source of loss amplifications. A recent outstanding example of cascading effects leading to considerable loss amplifications is the case of the Tohoku earthquake, Japan (Mori et al., 2011). Loss amplification can be a factor resulting from comparing the total losses caused by the chain of events triggered by an earthquake with the direct losses caused by the initial earthquake itself (Gasparini and Garcia-Aristizabal 2014).

Within the Integrated Crisis Management System developed in the CRISMA project, the general framework introduced in (Marzocchi et al. 2012) was adapted to design a concept model for cascading events assessment to support scenario-based analyses (Garcia-Aristizabal et al., 2012).

In the following section the concept model for cascading events assessment is firstly described, as well as the use and derivation of its essential components, namely the Cascading Events Scenarios (CES) and the Transition Matrix (TM) concept. Next, two example applications of the model are presented.

CONCEPT MODEL FOR CASCADING EVENTS ASSESSMENT

The concept of cascading effects in multi hazard assessment is a fundamental element in multi-risk problems. Marzocchi *et al.* (2012) identify the following main steps of the multi-risk assessment procedure: (1) Definition of the space–time window for the risk assessment and the metric for evaluating the risks; (2) Identification of the impending risks; (3) hazard scenarios covering all possible intensities and relevant hazard interactions; (4) Probabilistic assessment of each scenario; (5) Vulnerability and exposure assessment for each scenario, taking into account the vulnerability of combined hazards; and (6) Loss estimation.

Hence, having selected a study area for which multi-risk analysis is to be performed, a set of Cascading Effects Scenarios (CES) correlating adverse events from different sources has to be defined. Then, the possible scenarios can be quantified both in terms of expected impacts, thanks to the introduction of suitable simulation models for vulnerability and loss assessment, and by a probabilistic analysis considering the sequence of the events and suitably established Transition Matrices, as explained below.

Cascading Effects Scenarios (CES)

The relevant scenarios for a specific problem analysed can be identified adopting an “adaptive scenarios structuring strategy”, combining a forward logic and a backward logic approach. The former approach follows a forward logic in the sense that for each initiating event (e.g. a flood or an earthquake) identifies the possible outcomes (endpoints), following an event-tree-like structure. The backward logic strategy begins with and endpoint (effect) and works backwards to find the most likely causes of the effect, following a fault-tree-like structure. The combination of both approaches stems from the idea to iteratively use the forward logic and the backward logic approaches, and combine the results obtained in order to exhaustively identify all the relevant scenarios for the specific problem analysed.

Transition matrix concept

The transition matrix is an integrative element necessary for the probabilistic assessment of the occurrence and quantifying the expected damages for each cascading effect scenario. The transition matrix contains all the information of the conditional probabilities of having a given intensity of the triggered event given the intensity of the triggering event. Therefore, in general terms it can be an N x M matrix, a vector or a binary quantity, depending on the discretization of the intensity measures of both the triggered and triggering events.

Beyond the identification of scenarios, the main scientific problem for the assessment of cascading effects is to populate the probability values into the transition matrices. The values can be calculated using different sources of information, as for example databases of past events, using physical models, or based on expert opinion elicitations.

EXAMPLE APPLICATIONS FOR EARTHQUAKE TRIGGERED EVENTS

The example is based on the simulation of an earthquake (main triggering event) occurring in the surroundings of L'Aquila province (Abruzzo, Italy). In 2009 this region was struck by a Mw 6.3 earthquake, causing more than 300 victims, 1,500 injured and the temporary evacuation of more than 65,000 people.

Applying the described adaptive scenarios structuring strategy, a set of CES was identified, as shown in Fig. 1. Transition matrices for two worked examples (dashed red line) were derived using different approaches, e.g. employing physical and stochastic models for the triggered seismicity and electric pole fragility, elaborating results of experimental investigations for the assessment of forest fire ignition, or based on statistical elaborations of damages observed after past seismic events as for the case of the building seismic vulnerability.

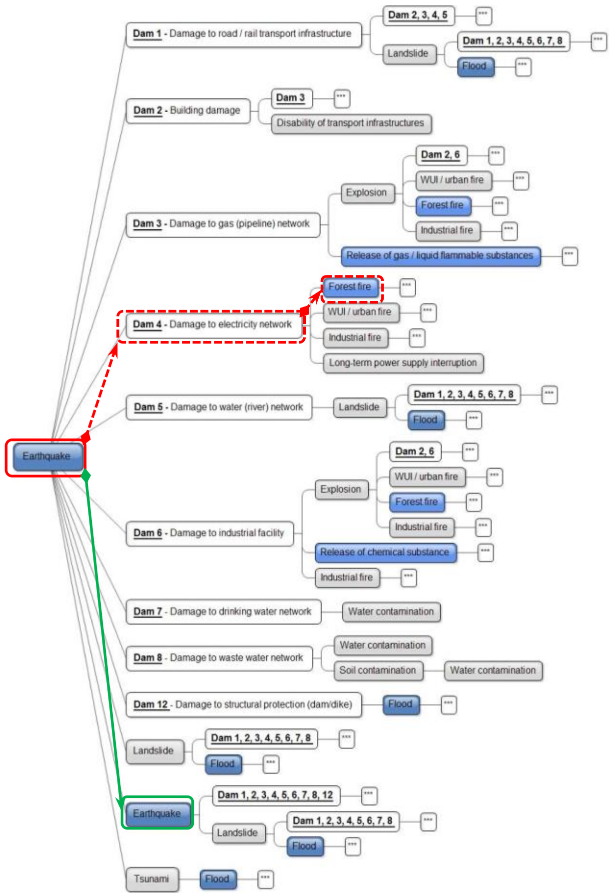


Figure 1. Diagram of the identified cascade event chains for Earthquake

The earthquake sequence case (EQ-EQ)

Among possible cascading effect scenarios, the possible activation of triggered seismicity and hence the possible sequence of earthquake events (see green arrow in Fig. 1), shall be considered. Forecasting the future behaviour of seismic sequences is not an easy task, and currently is a subject of intense research on applied seismology.

Assuming that a given model can be used to forecast in the short-term both the likely seismicity rates (e.g. in terms of number of events/day) and the expected spatial distribution, then short-term seismic hazard assessment can be performed and the expected damages caused by the triggered seismicity can be continuously updated.

Different kind of input data should be available to assess this scenario. First, an initial building inventory in the target area needs to be created. Fig. 2 shows a map of the study area as well as the grid representing the discretization of the domain for the impact assessment; for each grid element, the total number of buildings and the proportion of different seismic vulnerability classes are represented. Each building class corresponds with a specific set of vulnerability functions, as described by Damage probability matrices (Zuccaro and Cacace, 2015) or fragility curves (Polese et al., 2008).

Other input data necessary to build this example is the triggering earthquake and the consequent seismic sequence. Here, we simulate the occurrence of a main shock – aftershock sequence occurring in a zone located at the NW of L'Aquila city. The characteristics of the seismic sequence are simulated assuming seismicity rates, size-frequency distribution and spatial distribution of the events of similar past sequences in this region. In a near real-time application, these parameters can be set using the occurring seismic sequence.

The spatial distribution of the Peak Ground Acceleration (PGA) of the triggering event (in the example PGA_{max}=0.15 g) together with the fragility functions for the different building classes, can be used to calculate the probability of having building damages (e.g. collapse) in the target area (see Fig. 3). Using the triggered seismicity, short-term seismic hazard assessment can be performed using the data (i.e. spatial location, magnitude, shake maps) of the forecasted seismicity. The resulting transition probabilities for this scenario are the exceedance probabilities associated with different PGA values.

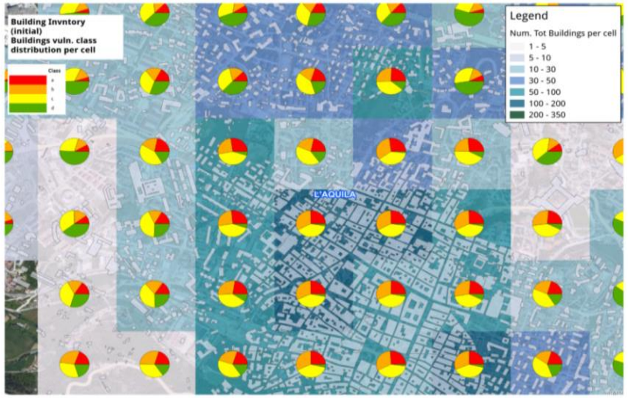


Figure 2. Building inventory in L'Aquila test case

Damage dependent seismic vulnerability and building impact

Usually, physical vulnerability to external events is considered almost stationary in time. However, there is the need to update vulnerability functions for elements at risk when the characteristics of such objects change and determine a varied (generally worsened) behaviour with respect to the hazardous event. Indeed, the repeating of damaging events can cause cumulative damage (Festa et al., 2005; Cosenza et al., 2009), that has to be properly considered for realistic impact assessment.

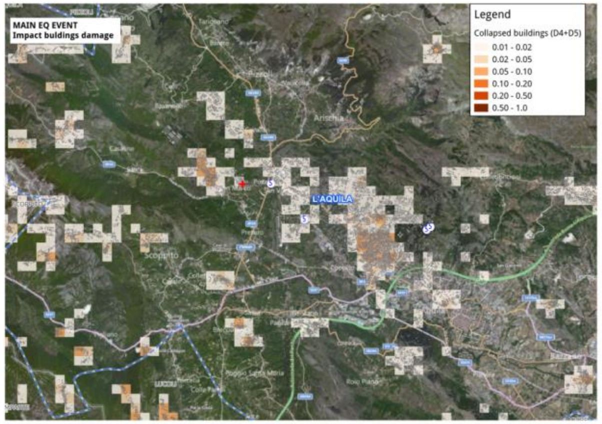


Figure 3. – Probability of having collapsed buildings in the target area after the main seismic event

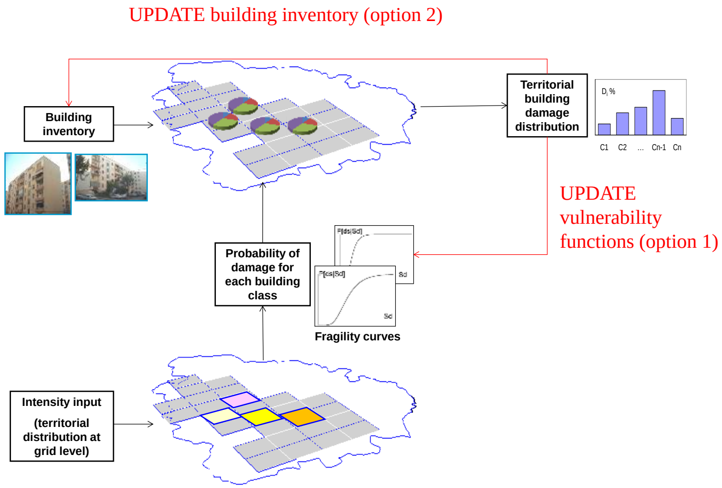


Figure 4. – The possible options for including TDV in the flow of analysis

Fig. 4 shows possible options for including Time-Dependent Vulnerability (TDV) in the flow of impact analysis. The first option entails the explicit consideration of the variation of fragility function, that may be directly determined as a function of the damage level that the generic element has suffered during the previous event. This first approach was applied for RC building classes (see e.g. Di Ludovico et al., 2013; Polese et al., 2013, 2014), but additional research is needed in order to assess vulnerability variation for Masonry type buildings. The second option, currently applied in CRISMA, entails the re-classification of the elements at risk (in pre-fixed vulnerability classes) considering the worsening of their behaviour due to damage (Zuccaro et al., 2008). Using the updated building inventory (after assessing the direct impact of the triggering earthquake) and the determined transition probabilities (exceedance probabilities associated with different PGA values), it is possible to calculate the expected impact of forecasted triggered seismic sequence.

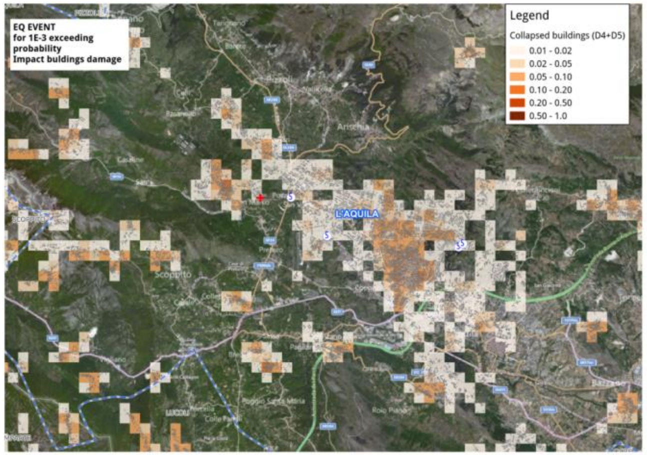


Figure 5. – Probability of having collapsed buildings after second earthquake

Fig. 5 shows the probability of having collapsed buildings in the target area for the earthquake-earthquake scenario, according with the characteristics of the seismic sequence triggered by the main seismic event. A comparison with the direct impacts expected after the main event (e.g. between Fig. 3 and Fig. 5) may be performed in order to assess the expected effects of the triggered seismicity.

The earthquake and forest fire case (EQ-FF)

Considering the same study area in the L'Aquila region, a further possible CES triggered by an earthquake is indicated by red arrows in Fig. 1. This scenario considers the possibility that, due to the seismic event, electricity poles of a medium-tension distribution line are subjected to excessive top displacements, causing the detachment and falling of the electric cable (damage to electricity network).

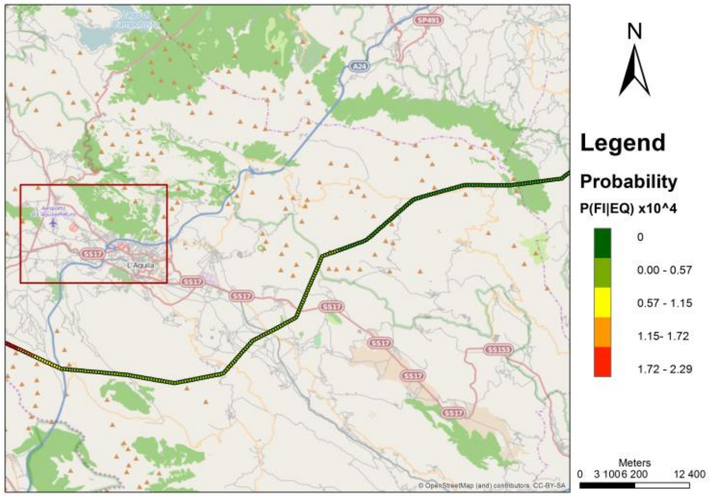


Figure 6. – **Probability of fire ignition due to an earthquake (max value 2.29·10^{-4})**

The falling of an electric cable can cause ignition and spreading of forest fires as further triggered events. Figure 6 shows the probability of fire ignition along an electric line due to the same triggering earthquake considered in the previous example. The red square evidences the extension of the study area for the EQ-EQ case.

Three categories of inputs must be available in order to assess the scenario: the location of the electricity network, the intensity distribution of the earthquake and the fuel cover in the area of interest. Moreover, the electric pole seismic fragility and the probability of having ignition after the electric cable failure shall be considered for probabilistic assessment.

Electric pole fragility

The electricity poles used in distribution lines may be classified based on the material, diameter and height. The tubular steel electric poles are very common and for this reason we concentrated on this typology; poles with height ranging from 9 to 12 m may be used either in low-voltage either in medium-voltage distribution lines.

Electric pole fragility represents the probability of attaining a limit value x_{LIM} of displacement at the pole top varying the intensity of the seismic input. x_{LIM} is represented as a fraction of a displacement x_{MAX} corresponding to the static application of the design force T_1; it is assumed that the attainment of x_{LIM} corresponds to the detachment of electric cable from the pole. In order to determine the probability of attaining x_{LIM}, an Incremental Dynamic Analysis (IDA) after selection of a set of representative records is performed (Vamvatsikos and Cornell, 2002). In order to perform the IDA, the pole is schematized as a Single Degree Of Freedom System with a concentrated mass on top, suitably characterized by stiffness k and elastic period T; 5% critical damping is assumed. Using the IDA analysis, fragility curves as that shown in Fig. 7 can be obtained. Fig. 7 shows the mean fragility curve obtained after analyzing tubular steel poles of heights 9, 10 and 12 m and considering x_{LIM} =0.5 x_{MAX}.

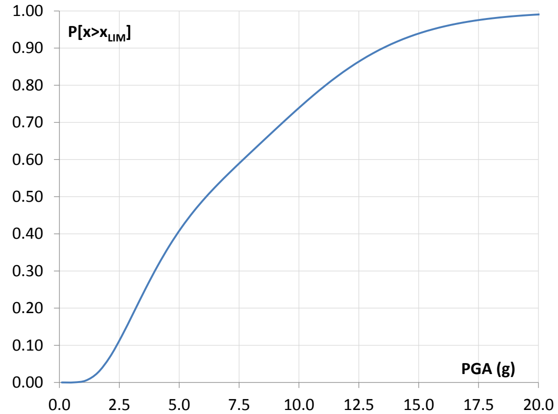
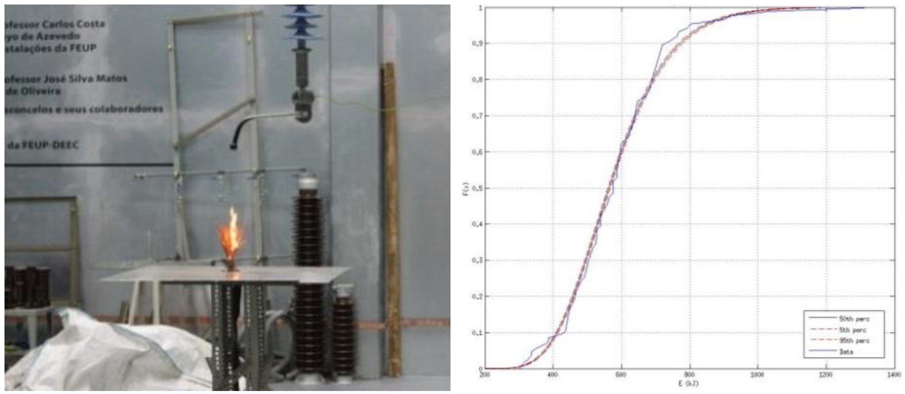


Figure 7. – Mean fragility curve for electric pole (x_{LIM} =0.5 x_{MAX})

Probability of ignition and forest fire

In order to determine the probability of having ignition after the electric cable failure, a statistical study was performed based on laboratory tests. Bouquets of dead pine needles (*Pinus pinaster*) and straw were experimentally exposed to an industrial electrical discharge of different voltages and intensities, and a constant power value of 300kVA (Fig. 8a). 67 tests were carried out with fuel moisture content ranging between 9.2 and 12.2%. The time elapsed to start an ignition of each bouquet under the electric discharge was counted and the necessary energy was calculated. The Log-normal function was selected as the best option to represent the distribution of the ignition probability of similar fuel beds as a function of the energy value of the electric discharge (Fig. 8b).



(a) (b)

Figure 8. – (a) Laboratory test; (b) cumulative distribution function of the Log-normal function selected as the best model describing the observations (μ=6.334 [6.329, 6.339] and σ=0.246 [0.243,0.250]).

Time dependent human exposure

Bringing the human factor into play within the overall framework of analyzing cascading event scenarios and assessing potential impacts, implies a further dimension of time-dependency and spatio-temporal dynamics. In the course of the development efforts under the CRISMA project umbrella, a dynamic population distribution model - *DynaPop* - has been designed, with the intention of applying it in a hazard context for human exposure analysis (Aubrecht et al. 2014). Dynamic human exposure patterns are crucial input for crisis management activities, including evacuation planning, casualty assessment as well as potential interrelated combinations thereof. *DynaPop* is therefore currently being implemented in a set of pilot studies including the l'Aquila study case presented in this paper, with the final output being a set of spatial grids illustrating population patterns in hourly intervals. Combining this with the spatial delineation of affected areas as provided by the respective hazard models, *DynaPop* allows deriving the actual or potential number of affected people.

With regard to the two different scenarios that are outlined above, *DynaPop* plays slightly different roles. For the EQ-EQ scenario, depending on the temporal intervals of the events, two aspects can be relevant. First of all, *DynaPop* provides an accurate starting basis to assess the number of people affected by the first shock, which is essential for a first-hand casualty assessment. If a second shock happens rather quickly after the first one, and the affected area is still in 'crisis mode' (i.e. people not having returned to their regular activity patterns), then *DynaPop* would not be directly applicable for the secondary impact assessment as it models and illustrates a regular non-crisis situation. With larger time intervals and a basic return-to-normal situation, *DynaPop* could again proof crucial for a secondary impact assessment that would then also account for the above-mentioned time-dependent structural vulnerability as input for refined casualty estimations. For the EQ-FF scenario, with fire potentially threatening the population, *DynaPop* would foremost serve as input for protective action planning. In fact, accounting for fire spread, potential at-risk-locations are continuously shifting, thus spatio-temporal dynamics become very relevant for crisis response (Aubrecht and Almeida, 2014). Having accurate population exposure patterns at hand, it can facilitate decision-making regarding sheltering vs. evacuating during the rapid response evaluation phase. High spatio-temporal granularity is crucial thereby in particular regarding dynamic estimation of evacuation times as well as shelter intake capacity modeling.

CONCLUSION

This paper presents a brief overview of the cascading effects model implemented within the Integrated Crisis Management System that is being developed in the EU CRISMA project. Main concepts underlying the model development are presented. In general, the evaluation of an entire path of a CES impacting a metropolitan area requires extensive knowledge about the area, including e.g. building inventory, systems, and suitable data to characterize the employed hazard models. Two case study applications demonstrate the applicability of the described cascading effects model, provided that necessary input data and auxiliary simulation models for impact assessment are available.

ACKNOWLEDGMENTS

This study was performed in the framework of EU CRISMA project. CRISMA is funded from the European Community's Seventh Framework Programme FP7/2007-2013 under grant agreement no. 284552.

REFERENCES

1. Aubrecht, C., M. Almeida (2014) Evaluating the benefits of spatio-temporal population dynamics data for protective action decision support in wildfire emergency management. In: D. X. Viegas (Ed.): 7th International Conference on Forest Fire Research (ICFFR). Proceedings (pp. 38-39). University of Coimbra, Portugal, November 17-20, 2014.
2. Aubrecht, C., K. Steinnocher, H. Huber (2014) DynaPop – Population distribution dynamics as basis for social impact evaluation in crisis management. In: S.R. Hiltz, M.S. Pfaff, L. Plotnick, P.C. Shih (Eds.): ISCRAM 2014 Conference Proceedings, 11th International Conference on Information Systems for Crisis Response and Management (pp. 319-323). University Park, PA, USA, May, 2014.
3. Cosenza, E., Manfredi, G., Polese, M., (2009) A simplified method to include cumulative damage in the seismic response of SDOF systems, *Journal of Engineering Mechanics*, ASCE, 135 (10), 1081-1088
4. Di Ludovico, M., Polese, M., Gaetani d'Aragona, M., Prota, A., Manfredi, G. (2013) A proposal for plastic hinges modification factors for damaged RC columns, *Engineering Structures* 2013; 51:99-112.
5. Festa, G., Zollo, A., Manfredi, G., Polese, M. and Cosenza, E. (2004) Simulation of the Earthquake Ground Motion and Effects on Engineering Structures During the Pre-eruptive Phase of an Active Volcano, *Bulletin of the Seismological Society of America*, 94, 2213-2221
6. Garcia-Aristizabal, Polese, M., Zuccaro, G., A., Almeida, M., Reva, V., Viegas, D., Rosqvist, T., Porthin, M., (2013) D42.1 – Dynamic scenario concept models, deliverable of the EU CRISMA project

7. A. Garcia-Aristizabal, P. Gasparini, and G. Uhinga (forthcoming-2015). Multi-risk assessment as a tool for decision-making. Future Cities, Vol. 4, Pauleit et al., Eds., Springer, ISBN 978-3-319-03984-8.
8. Garcia-Aristizabal, A., Almeida, M., Aubrecht, C., Polese, M., Mário, L., Viegas, D., Zuccaro, G. (2014) Assessment and Management of Cascading Effects Triggering Forest Fires, *VII International Conference on Forest Fire Research*, D. X. Viegas (Ed.), Coimbra, Portugal, 17-20 November 2014. doi: 10.14195/978-989-26-0884-6_117
9. P. Gasparini and A. Garcia-Aristizabal (2014). Seismic Risk Assessment, Cascading Effects. In: Beer M., Patelli E., Kougioumtzoglou I., Au I. (Ed.) Encyclopedia of Earthquake Engineering, SpringerReference, p. 1-20. Springer-Verlag Berlin Heidelberg. ISBN: 978-3-642-36197-5 DOI: 10.1007/978-3-642-36197-5_260-1
10. Marzocchi, W., Garcia-Aristizabal, A., Gasparini, P., Mastellone, M.L. & Ruocco, A.D. (2012). Basic priciples of multi-risk assessment: a case study in Italy, *Natural Hazards*, 62 (2), 551-573
11. Mori, N., T. Takahashi, T. Yasuda, and H. Yanagisawa (2011), Survey of 2011 Tohoku earthquake tsunami inundation and run-up, Geophys. Res. Lett., 38, L00G14, doi:10.1029/2011GL049210
12. Polese, M., Verderame, G. M., Mariniello, C., Iervolino, I., Manfredi, G. (2008) Vulnerability analysis for gravity load designed RC buildings in Naples – Italy, *Journal of Earthquake Engineering*, 12 (S2), 234-245
13. Polese, M., Di Ludovico, M., Prota, A., Manfredi, G. (2013) Damage-dependent vulnerability curves for existing buildings. *Earthquake Engineering Structural Dynamics*; 42 (6): 853-870, DOI: 10.1002/eqe.2249.
14. Polese, M., Marcolini, M., Zuccaro, G., Cacace, F. (2014) Mechanism Based Assessment of Damaged- Dependent Fragility curves for RC building classes, *Bulletin of Earthquake Engineering*, in press, DOI 10.1007/s10518-014-9663-4
15. Vamvatsikos, D.; Cornell, A. (2002). Incremental dynamic analysis. *Earthquake Engineering and Structural Dynamics*. 31 (3), 491-514
16. Zuccaro, G., Cacace, F., Spence, R.J.S., Baxter, P.J. (2008). Impact of explosive eruption scenarios at Vesuvius, *Journal of Volcanology and Geothermal Research*, Vol. 178, pp. 416–453.
17. Zuccaro, G., Cacace, F. (2015). Seismic vulnerability assessment based on typological characteristics. The first level procedure “SAVE”, Journal *of Soil dynamics and Earthquake Engineering*, DOI 10.1016/j.soildyn.2014.11.003
18.