Bollettino di Geofisica Teorica ed Applicata Vol. 55, n. 1, pp. 227-237; March 2014
DOI 10.4430/bgta0116

Can earthquakes trigger serious industrial accidents in Italy? Some considerations following the experiences of 2009 L'Aquila (Italy) and 2012 Emilia (Italy) earthquakes

S. Grimaz

SPRINT-Lab, Dipartimento di Chimica Fisica Ambiente, Università di Udine, Italy

(Received: March 27, 2013; accepted: July 8, 2013)

ABSTRACT The earthquake in Japan on March 11, 2011, provoking the accident at the nuclear plant of Fukushima, highlighted, unequivocally, as strong seismic events can provoke major accidents. On the other hand the damage observed in recent earthquakes in Italy (L'Aquila, 2009 and Emilia, 2012) pointed out the high seismic vulnerability of industrial plants. This paper provides an analysis on the possibility that earthquakes can trigger serious industrial accidents (Na-Tech risk), referring in particular to the Italian territory, where many Seveso establishments are located. The results show a high risk and suggest that urgent preventative actions are needed. For this purpose, a change of the seismic safety paradigm, moving from the classical sectorial and reductionist approach to the holistic and interdisciplinary one, is required.

Key words: L'Aquila earthquake, central Italy, Na-Tech risk.

1. Introduction

The accident at the nuclear plant of Fukushima after the March 11, 2011 powerful earthquake in Japan has clearly shown that the impact of earthquakes on industrial plants and life-lines may trigger events that could produce relevant hazardous scenarios or critical inoperability of safety facilities (Grimaz and Slejko, 2014). An important question arises from that experience: can an earthquake provoke serious accidents also in Italy? To answer this question, a critical reading of the impact of 2009 L'Aquila (Italy) and 2012 Emilia (Italy) earthquakes on industrial facilities and life-lines, as they appeared to the rescue services immediately after the event, are here presented together with some considerations in terms of lessons learnt, also useful for preventative risk mitigation purposes. This has been possible because few days after both those earthquakes, a research team of the University of Udine, jointly to engineers of the Italian National Fire Department (Corpo Nazionale dei Vigili del Fuoco: CNVVF), investigated and analysed the damage occurred to industrial facilities and life-lines in order to identify major and recursive criticisms and derive useful "lessons learnt" for safety improvement (Grimaz and Maiolo, 2010) and for the definition of short term countermeasures, necessary for managing the emergency operations in safe conditions (Grimaz, 2011).

2. The earthquake of L'Aquila, 2009

On April 6, 2009, at 3:32 a.m. (local time), a 6.3 M_W earthquake occurred in central Italy, with epicentre located 7 km NW of the town of L'Aquila, with depth of approximately 8 km on a normal fault on the Apennine mountains. Even if the 6.3 M_W 2009 L'Aquila earthquake is classifiable as moderate, L'Aquila and its surroundings, located in the near-field area of the earthquake, were affected by a level of ground motion capable of provoking significant damage to industrial facilities and life-lines present in that area. *PGA* higher than 0.6 g was recorded in near field [for an accurate analysis of the destructive potential of l'Aquila 2009 earthquake see: Masi *et al*. (2011)].

2.1. Damage to industrial facilities and lifelines in the epicentral area

After the earthquake, three industrial zones (Bazzano-Paganica, Pile and Sassa), located in the surrounding area of L'Aquila, were inspected and specific and recursive damage was observed (Grimaz and Maiolo, 2011).

In these areas there are high-tech, pharmaceutical, construction, mechanical and manufacturing industries. The most diffuse typology of building is represented by precast concrete structures using precast panels, reinforced frames with concrete block walls and steel or light metal frames with precast panel walls.

The damage observed was mainly concentrated in non-structural elements (e.g., partitions and ceiling tiles) and contents. The criticisms were related to the connection between the secondary elements and the structure. The inadequate anchorage between the wall panels and the roof and floor framing members in the precast-concrete buildings resulted in the collapse of the walls. Some structural damage to beams and columns was also observed. In this case the criticisms concerned the weakness of the joints and, in particular, the unseating effects (considerable movements of the beam and column corbel support) were observed. Other recursively criticisms regarded the first step of "soft-story" behaviour that could lead to building collapses in case of a stronger earthquake.

Furthermore, the equipment of the industrial plants moved and/or collapsed, causing damage and major business interruptions, because it was not anchored or adequately braced to avoid relative movements during the earthquake.

A particular case of damage was observed in a chemical facility located in the industrial area of Bazzano-Paganica, 7 km south far from L'Aquila town, where three tall steel silos storing polypropylene beads suffered severe damage. The silos collided with the adjacent precast warehouse, partially crushing the concrete wall and leaving the imprint of the impact. The silos also crumpled at their bases (Fig. 1).

The damage observed on life-lines highlights the primary criticisms on the gas distribution (Esposito *et al*., 2011). A lot of gas pipelines were damaged or broken because the buildings were heavily damaged. Many RC buildings suffered high deformation caused by the plasticization of the beam-pillar connections, and some of them, with a "soft-story", collapsed completely. Since the majority of flats, houses and apartments were served by autonomous boilers, a lot of gas pipelines were installed outside the buildings, on the perimeter walls, and many of them were broken or damaged. This caused significant releases of gas, but fortunately, no fires started.

Fig. 1 - L’Aquila earthquake: damage to, and caused by, silos at VIBAC facility in the Bazzano industrial area, 7 km south far from L’Aquila town.

Natural gas and electricity supplies were cut-off in the areas of severe damage, mainly in downtown of L’Aquila, and several users were disconnected.

Utility networks for water, electricity and phone services were all briefly interrupted because of the damage caused by the earthquake. The damage was localized and, after minor repairs and reconfigurations, all services were fully functional within a day. A pipe-break in the main water supply of the area was the most important damage to the water system. A high pressure water pipeline broke at the crossing of the Paganica fault, due to a co-seismic movement within the main event. There were also some pipe breaks in the distribution system, and a lot of them had to be repaired in order to provide water to emergency shelters and temporary accommodation.

Phone services were interrupted for a short time because of power failure. Problems were solved by putting emergency generators into service.

The damage to transport infrastructure was minimal. The only collapsed structure was the bridge over the Aterno River, along a secondary road to Fossa (AQ). Immediately after the earthquake both highways A24 and A25, connecting the Tyrrhenian and Adriatic coasts, were closed for an inspection of the viaducts, but reopened a few days later.

A number of regional and provincial roads were partially closed, mainly because of land and rock slides and settlements induced by the earthquake. These interruptions caused some transit difficulties for the emergency rescue services.

2.2. Lessons learnt from 2009 L'Aquila earthquake

The post-earthquake inspections showed as L'Aquila earthquake, despite the moderate magnitude, caused extensive damage to industrial facilities and life-lines. The industrial buildings were non-ductile concrete and new precast constructions that suffered damage on structural and non-structural elements and on equipment. This typology of industrial buildings, widely diffused in Italy, has shown significant seismic vulnerabilities both in the structure and the equipment. The high level of vulnerability of this typology of buildings has been afterwards underlined also by Toniolo and Colombo (2012).

From the damage observed in L'Aquila, it can be said that earthquakes of around 6.3 M_W, will possibly, or are likely to result in serious industrial accidents, should dangerous substances be stored in pre-cast buildings.

Furthermore, in comparison with the past, when the use of gas was less diffuse, nowadays the probability of gas releases and the possibility of subsequent fires are increased. This suggests the need of introducing specific fire precaution measures.

Considering that a similar situation could occur also in other areas of the country in case of an earthquake, the Italian National Fire Department set up a specific working group with the aim of defining technical guidelines for reducing seismic vulnerability, in particular, of gas facilities and fire prevention and protection systems (CNVVF, 2012).

3. Observations and confirmations after the 2012 Emilia earthquake

On May 20, 2012 at 04:03 (local time) an earthquake of M_W 5.86 struck the Pianura Padana Emiliana (northern Italy). The epicentre was localized between the towns of Mirandola, Finale Emilia, Poggio Rusco and Bondeno with a hypocentre depth of 6 km. On May 29 at 9:00 (local time), a second main shock of M_W 5.66 occurred, with epicentre moved westwards from the first main shock (closer to Mirandola) and produced vertical and horizontal *PGA* up to 0.7 g and 0.3 g respectively, in the epicentral area.

The area, highly industrialized, was heavily damaged. A lot of roofs of precast buildings collapsed causing deaths and the complete interruption of the activities (Fig. 2). The scenario confirmed the high vulnerability of the precast industrial buildings, as evidenced after the L'Aquila earthquake. In fact, the most diffuse structural typologies are:

a) precast system, in simple or multi-storey buildings, in which structural elements were made of precast reinforced concrete;

b) mix-materials buildings, made of pre-stressed concrete pillars, located in the central part of the building, and masonry walls along the perimeter.

The presence of heavy equipment or photovoltaic facilities installed on the roof aggravated the vulnerability of the buildings. The damage scenario was extremely more extended and severe than in L'Aquila. A lot of life-lines went and remained out of service. A detailed description of industrial building damage can be find in Marzo *et al*. (2012) and Savoia *et al*. (2012).

Definitely, all the considerations made after the L'Aquila earthquake were systematically confirmed and accentuated by the impact analyses of the Emilia earthquake in 2012, which showed, in particular, the high vulnerability of facilities and equipment and the risk related to the release of dangerous substances, like gas or chemicals, caused by ruptures of pipelines or

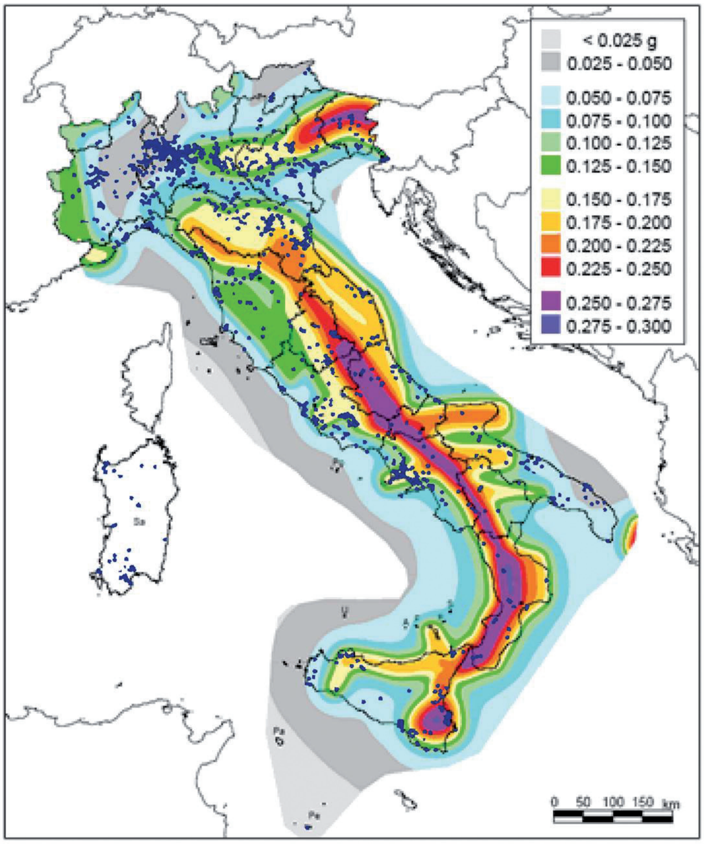
Fig. 2 - Emilia earthquake: heavy damage to industrial buildings in the epicentral area. General collapse of roof of precast system structures destroyed the internal facilities.

storage tanks. Despite the fact that a lot of facilities and pipelines broke due to the collapse of industrial buildings in which they were installed, fortunately, no dangerous events were recorded. This was probably because the earthquake occurred at night when almost no hazardous activities take place.

It is worth to observe that few weeks after the second main shock, the Italian National Commission of Major Risks, in a statement released by the Italian Prime Minister's Office on the situation in Emilia, said: "In the event of a resumption of seismic activity in the area already affected by the earthquake sequence in progress, the probability of a segment activation between Finale Emilia and Ferrara, with events comparable to the major events recorded in the sequence, is significant". In that area there is the petrochemical plant of Ferrara; therefore, the potential impact on a Seveso plant was one of the major concerns for the emergency management. Fortunately, the event did not occur, but this fact evidenced that the seismic vulnerability of facilities and of Seveso establishments as well, are fundamental elements to take into account in order to define adequate countermeasures.

4. Seismic events and Seveso establishments in Italy

Considering the experiences and the lessons learnt from the last recent two main earthquakes in Italy (L'Aquila and Emilia), a question arises: what would it happen if industrial or chemical plants with a high risk of major accident were located in the epicentral area of an earthquake? This question should generate concern because most of Italian territory is seismic and this typology of facilities presents a lot of vulnerabilities. In fact, it is well known in literature that industrial equipment and systems can suffer structural damage when hit by earthquakes and can provoke serious accidents as fire, explosions and dispersion of toxic substances (MHIDAS, 2001; Krausmann *et al*., 2011).



SEVESO establishments in Italy

Region	N.
Abruzzo	26
Basilicata	9
Calabria	17
Campania	70
Emilia Romagna	99
Friuli Venezia Giulia	34
Lazio	69
Liguria	34
Lombardia	288
Marche	16
Molise	8
Piemonte	103
Puglia	43
Sardegna	42
Sicilia	71
Toscana	62
Trentino Alto Adige	17
Umbria	17
Valle d'Aosta	6
Veneto	112
Total	**1143**

Typology	%
Chemical and petrolchemical plant	26.20
Storage of liquified gases	24.30
Electroplating	10.34
Storage mineral oils	8.44
Explosives production and storage	7.80
Production and storage technical gases	3.81
Toxic substances storage	3.08
Pesticide storage	2.99
Steel and metallurgical plants	2.72
Underground storages	1.09
Treatment and recovery facilities	1.81
Petroleum refining	1.54
Distillation	1.45
Power plant	0.45
Other	3.35

Seismic zone (acceleration)	N.	%
1 ($a_g > 0.25$)	37	3.2
2 ($0.15 < a_g \leq 0.25$)	333	29.1
3 ($0.05 < a_g \leq 0.15$)	287	25.1
4 ($a_g \leq 0.05$)	486	42.6

Fig. 3 - Seveso establishments in Italy. On the upper panel the location of Seveso establishments (blue dots) on the seismic hazard map (Gruppo di Lavoro MPS, 2004) showing values of *PGA* having 10% probability of exceedence in 50 years (T_R = 475 years). Tables show the number of establishments in each region, the percentage of establishments typology at national level and the distribution of establishments in the different seismic zones [data elaborated from M.S. (2010) and M.A.T.M.A. (2012)].

In Italy there are more than 1100 Seveso establishments (i.e., establishments where certain quantities of dangerous substances are present, as defined in http://glossary.eea.europe.eu as). About 1/3 of them are located in areas with moderate or high seismic hazard. Fig. 3 shows the distribution of establishments on the Italian territory, indicates the percentage of different typologies of establishments and reports the number and percentage of establishments in the four seismic zones.

The most diffuse activities are chemical and petrochemical plants, storage of liquefied gases and mineral oil storages. A great number of Seveso establishments are located in areas in which the estimated level of acceleration on rock (a_g) exceeds 0.15 g with probability of exceeding equal to 10% in 50 years.

In order to estimate the expected damage of equipment components following an earthquake, several approaches are possible. A correlation linking the conditional probability of the specific Level of Damage (LD) to *PGA* of the earthquake is required. In the conventional approach of probabilistic analysis of damage caused by seismic events, fragility curves are used to assess the resistance of a structure to a given *PGA* (O'Rourke *et al*., 2000; Talaslidis *et al*., 2004). However the probit functions (Finney, 1971) have been more widely used in order to derive vulnerability models for industrial equipment (Salzano *et al*., 2003, 2009; Fabbrocino *et al*., 2005; Campedel *et al*., 2008) but in some cases also for residential buildings (Grimaz, 2009). Probit analyses were carried out on the basis of information of seismic damage observed on different items and collected in databases (MHIDAS, 2001; Di Cecca and Grimaz, 2009). Advantage and drawbacks of fitting empirical data by fragility curves and probit functions are presented in Lallemant and Kiremidjian (2013).

More specifically, the probit variable *Y* represents a dose-response relationship and gives a specific quantal response as a function of the intensity of the variable *V* (the dose) through a linear correlation with the logarithm of *V*:

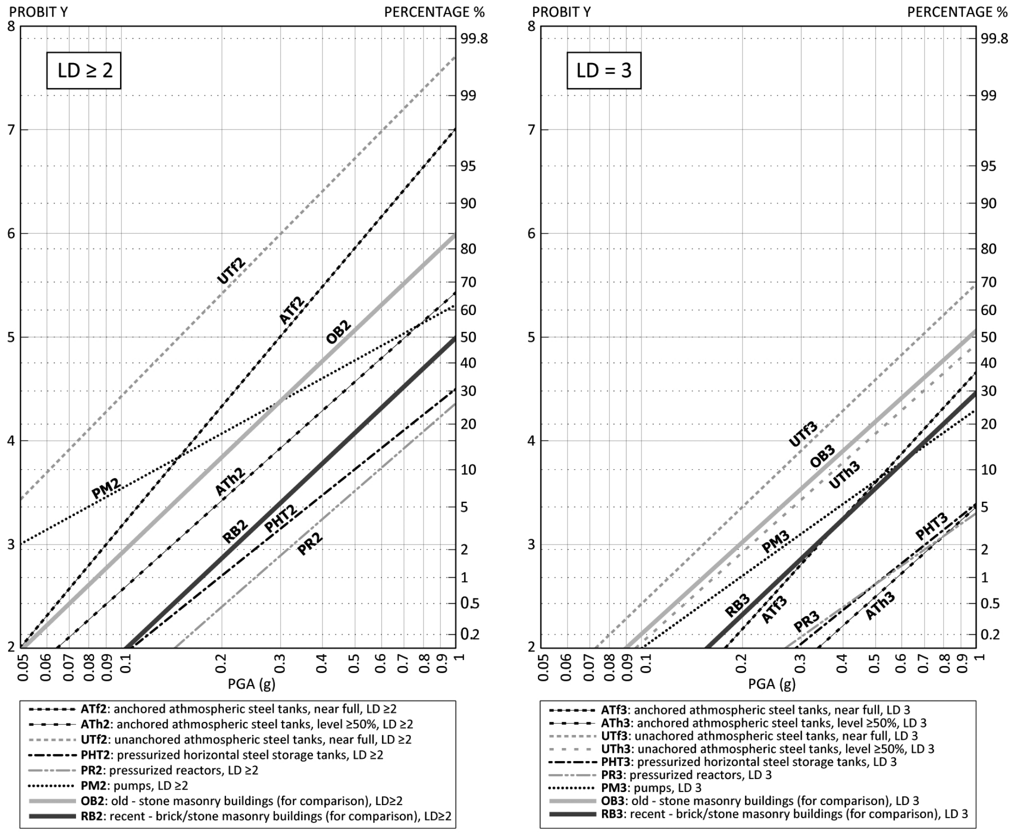
$$Y = k_1 + k_2 \cdot lnV. \qquad (1)$$

For the case of seismic action, the dose is considered as the seismic *PGA* (g) whereas the effect is considered as LD, either as the structural damage or, more appropriately, the loss of containment or the "out of service" of industrial equipment hit by an earthquake. The variable *Y* can be directly compared with the actual failure probability *p*, or the percentage *P* of target that suffers the specific LD, by means of the following equations, respectively (CCPS, 2000; Vilchez *et al*., 2001):

$$p = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{Y-5} \left(e^{-\frac{V^2}{2}} \right) dV \qquad \text{(Vilchez } et\ al.\text{, 2001)} \qquad (2)$$

$$P = 50 \left[1 + \frac{Y-5}{|Y-5|} erf \left(\frac{|Y-5|}{\sqrt{2}} \right) \right] \qquad \text{(CCPS, 2000).} \qquad (3)$$

For a quantitative estimation of the potential of observing severe accidents triggered by earthquakes in Italy, it is interesting to compare probit equations of damage between industrial



THRESHOLD OF DAMAGE
LD 2 = significant structural damage - significant release of hazardous substances - out of service of equipment
LD 3 = total collapse of structure - sudden loss of containment of the entire vessel - heavy damage of equipment

$$Y = k1 + k2 \cdot \ln PGA(g)$$

INDUSTRIAL EQUIPMENT [1]		Cod.	LD	Probit coefficients k1	Probit coefficients k2
Anchored atmospheric steel tanks	near full	ATf2	≥2	7.01	1.67
		ATf3	3	4.66	1.54
	level ≥50%	ATh2	≥2	5.43	1.25
		ATh3	3	3.36	1.25
Unanchored atmospheric steel tanks	near full	UTf2	≥2	7.71	1.43
		UTf3	3	5.51	1.34
	level ≥50%	UTh3	3	4.93	1.25
Pressurized horizontal steel storage tanks		PHT2	≥2	4.50	1.12
		PHT3	3	3.39	1.12
Pressurized reactors		PR2	≥2	4.36	1.22
		PR3	3	3.30	0.99
Pumps		PM2	≥2	5.31	0.77
		PM3	3	4.30	1.00
RESIDENTIAL BUILDINGS [2] (for comparison)	*Old - stone masonry*	*OB2*	*≥2*	*5.99*	*1.34*
		OB3	*3*	*5.06*	*1.27*
	Recent - brick/stone masonry	*RB2*	*≥2*	*4.99*	*1.32*
		RB3	*3*	*4.46*	*1.33*

(1) from Campedel et al., 2008.
(2) from Grimaz, 2009.

Fig. 4 - On the top: graphs of comparison among probit equations for various industrial equipment and residential masonry buildings for two thresholds of damage. On the bottom: the table with the coefficients of each probit equation.

equipment and residential houses proposed in the works above mentioned (Fig. 4).

The graphs in Fig. 4, in particular, evidence that the probability that an earthquake will trigger a serious accident on equipment in Seveso establishment is not negligible. A comparison of value of k_1 e k_2 of Fig. 4 for different items gives direct and useful information on the gravity of the accidental event.

In particular, it is worth noting that the probability that an earthquake will trigger major dangerous substance releases from anchored and unanchored atmospheric steel tanks is higher than the probability that it will cause significant structural damage on old masonry buildings. For instance, if *PGA* is equal to 0.15 g, the probability of observing significant releases of dangerous substances from full tanks will be higher than 50% if unanchored and 15% if anchored, while, for the same value of *PGA*, the probability of observing serious damage in old and recent masonry buildings will be 5% and 1% respectively.

These observations permit to appreciate the importance of the 15th "whereas" of the 2012/18/EU Directive (Seveso III): "In order to demonstrate that all that is necessary has been done to prevent major accidents, and to prepare emergency plans and response measures, the operator should, in the case of establishments where dangerous substances are present in significant quantities, provide the competent authority with information in the form of a safety report. That safety report should contain details of the establishment, the dangerous substances present, the installation or storage facilities, possible major accident scenarios and risk analysis, prevention and intervention measures and the management systems available, in order to prevent and reduce the risk of major accidents and to enable the necessary steps to be taken to limit the consequences thereof. The risk of a major accident could be increased by the probability of natural disasters associated with the location of the establishment. This should be considered during the preparation of major-accident scenarios."

Nevertheless, it is worth noting that Italian laws, still nowadays, do not include any specific rule about the necessity of assessing, for those plants, the risk of major accidents caused by seismic events.

5. Considerations in term of prevention and conclusions

It is hoped that industrial seismic damage, observed after the L'Aquila and Emilia earthquakes, suggests a better integration of seismic aspects in the laws and codes for industrial plants design and reinforcement, in order to assess and reduce possible NaTech risks (technological accidents induced by natural events) for such facilities. Furthermore, in order to avoid serious accidents like fires or explosions, the attention to NaTech risks must be extended from Seveso establishments to other industrial and residential facilities and, in particular, to gas storage tanks, pipelines and utilities.

In any case, it is necessary to highlight the low seismic resistance of the precast-concrete buildings, and the criticisms related to non-structural elements and equipment. The physical damage related to these vulnerabilities can cause releases of dangerous substances and the activation of accidents. More stringent seismic design is needed for these structures also in order to avoid damage on equipment or facilities. Other element of concern is the reliability of the cooling systems of reactors in chemical industries, particularly when the earthquake provokes the interruption of the main pipelines of water furniture.

Some indications in terms of possible provision could be defined: greater attention must be paid in designing effective connection between primary and secondary elements in the precast concrete buildings and in controlling the relative deformation of the various parts of the building structures. Specific attention must be addressed to pipelines in correspondence to fault crossing points and to the redundancy of safety systems. It is also necessary to implement more precautions on the anchorage of equipment and to avoid destructive interactions with other components. Furthermore, automatic valves triggered by accelerometer should be installed on the gas pipelines outside the buildings. This will reduce drastically the risk of fire because an immediate blockage of the gas supply is automatically activated in the case of strong earthquake.

Finally, taking into account the observations on damage provoked by the L'Aquila and Emilia earthquakes, it is possible to answer the question stated in the title of the paper: Yes, unfortunately, earthquakes could trigger serious accidents also in Italy, not only in Seveso establishments!

Therefore, possibly before the next severe earthquake, greater attention must be addressed to NaTech problems, both in major risk assessment processes and seismic codes. Within the risk assessment and management framework, higher attention must also be addressed to the resilience of affected systems and, in particular, to the role of life-lines networks in supporting the emergency management and in facilitating the response and the recovery phases after an earthquake. This requires to take into account the interdependence between natural and technological hazards in the policies of risk reduction, considering seismic safety as an interdisciplinary problem that has to be assessed and managed using a holistic approach rather than the reductionist and sectorial one, nowadays, generally used.

Acknowledgements. The author of this paper, in both the emergencies of L'Aquila, 2009 and Emilia, 2012, worked jointly with the Italian National Fire Department (CNVVF) as scientific coordinator of the specialist unit responsible for damage assessment and short term countermeasures definition. This permitted to observe the damage since the first phase after the main shocks and to recognise and evaluate safety problems induced by the earthquake in industrial facilities. Sincere thanks go to the colleagues all of the CNVVF and the University of Udine for the effective and profitable work done together. Special thanks to the reviewers for their useful suggestions that have helped to improve this paper.

REFERENCES

Campedel M., Cozzani V., Garcia-Agreda A. and Salzano E.; 2008: *Extending the quantitative assessment of industrial risks to earthquake effects*. Risk Anal., **28,** 1231-1246.

CCPS; 2000: *Effect models in guideline for chemical process quantitative risk analysis*. In: Am. Inst. Chem. Eng., 2nd ed., New York, NY, USA, pp. 244-249.

CNVVF; 2012: *Linee di indirizzo per la riduzione della vulnerabilità sismica degli impianti antincendio*. Ministero dell'Interno, Corpo Nazionale dei Vigili del Fuoco, Grimaz S. (coord.), Roma, Italy, 47 pp., in Italian. <www.vigilfuoco.it/aspx/download_file.aspx?id=12215>.

Di Cecca M. and Grimaz S.; 2009: *The new Friuli Earthquake Damage (Fr.E.D.) database*. Boll. Geof. Teor. Appl., **50**, 277-287.

Esposito S., Elefante L. and Iervolino I.; 2011: *Addressing ground-shaking-induced damage of the gas distribution network in the 2009 L'Aquila earthquake*. In: Proc. XIV Convegno ANIDIS - L'Ingegneria sismica in Italia, Paper n. 1014, ISBN 978-88-7522-040-2.

Fabbrocino G., Iervolino I., Orlando F. and Salzano E.; 2005: *Quantitative risk analysis of oil storage facilities in seismic areas*. J. Hazard. Mater., **12**, 61-69.

Finney D.J.; 1971: *Probit analysis (3rd ed.)*. Cambridge University Press, Cambridge, UK, 333 pp.

Grimaz S.; 2009: *Seismic damage curves of masonry buildings from Probit analysis on the data of the 1976 Friuli earthquake (NE of Italy)*. Boll. Geof. Teor. Appl., **50**, 289-304.

Grimaz S.; 2011: *Management of urban shoring during a seismic emergency: advances from the 2009 L'Aquila (Italy) earthquake experience*. Boll. Geof. Teor. Appl., **52**, 341-355, doi:10.4430/bgta0005.

Grimaz S. and Maiolo A.; 2010: *The impact of 6th April 2009 L'Aquila earthquake (Italy) on the industrial facilities and lifelines. Consideration in terms of NaTech risk*. Chem. Eng. Trans., **19**, 279-284, doi:10.3303/CET1019046.

Grimaz S. and Maiolo A.; 2011: *Can the earthquakes trigger serious accidents in Italy? Some lessons from the 2009 L'Aquila earthquake*. In: Atti 30° Convegno Gruppo Nazionale di Geofisica della Terra Solida, Trieste, Italy, pp. 211-214.

Grimaz S. and Slejko D.; 2014: *Seismic hazard for critical facilities*. Boll. Geof. Teor. Appl., **55**, 3-16.

Gruppo di Lavoro MPS; 2004: *Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003*. Rapporto Conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma, 65 pp. + 5 appendixes, http://zonesismiche.mi.ingv.it/mappa_ps_apr04/italia.html.

Krausmann E., Cozzani V., Salzano E. and Renni E.; 2011: *Industrial accidents triggered by natural hazards: an emerging risk issue*. Nat. Hazards Earth Syst. Sci., **11**, 921-929.

Lallemant D. and Kiremidjian A.; 2013: *Fitting fragility curves to empirical data*. GEM Foundation, Technical Report 2013-X, Pavia, Italy, 33 pp.

Marzo A., Marghella G. and Indirli M.; 2012: *The Emilia - Romagna earthquake: damages to precast/prestressed reinforced concrete factories*. Ingegneria Sismica, **29**, 132-147.

Masi A., Chiauzzi L., Braga F., Mucciarelli M., Vona M. and Ditommaso R.; 2011: *Peak and integral seismic parameters of L'Aquila 2009 ground motions: observed vs code provision values*. Bull. Earthquake Eng., **9**, 139-156.

M.A.T.M.A.; 2012: *Inventario nazionale degli stabilimenti suscettibili di causare incidenti rilevanti ai sensi dell'art.15 comma 4 del D.Lgs 17/99 n. 334 e s.m.i*. Ministero dell'Ambiente e della Tutela del territorio e del mare, ISPRA-Servizio rischio industriale, <www.salute.gov.it>.

MHIDAS; 2001: *Major Hazard Incident DAta Service*. UK Atomic Energy Authority (accessible on OSH-ROM, Silver Platter International).

M.S.; 2010: *Relazione annuale al PNI*. Ministero della Salute, Roma, Italy, <www.salute.gov.it>.

O'Rourke M.J., Eeri M. and So P.; 2000: *Seismic fragility curves for on-grade steel tanks*. Earthquake Spectra, **16**, 801-815.

Salzano E., Iervolino I. and Fabbrocino G.; 2003: *Seismic risk of atmospheric storage tanks in the frame work of quantitative risk analysis*. J. Loss Prev. Process Ind., **16**, 403-409.

Salzano E., Garcia Agreda A., Di Carluccio A. and Fabbrocino G.; 2009: *Risk assessment and early warning systems for industrial facilities in seismic zones*. Reliab. Eng. Syst. Saf., **94,** 1577-1584.

Savoia M., Mazzotti C., Buratti N., Ferracuti B., Bovo M., Ligabue V. and Vincenzi L.; 2012: *Damages and collapses in industrial precast buildings after the Emilia earthquake*. Ingegneria sismica, **29**, 120-131.

Talaslidis D.G., Manolis G.D., Paraskevopoulos E., Panagiotopoulos C., Pelekasis N. and Tsamopoulos J.A.; 2004: *Risk analysis of industrial structures under extreme transient loads*. Soil Dyn. Earthquake Eng., **24**, 435-438.

Toniolo G. and Colombo A.; 2012: *Precast concrete structures: the lessons learned from the L'Aquila earthquake*. Struct. Concr., **13**, 73-83.

Vilchez J.A., Montiel H., Casal J. and Arnaldos J.; 2001: *Analytical expression for the calculation of damage percentage using Probit methodology.* J. Loss Prev. Process Ind., **14**, 193-197.

Corresponding author: Stefano Grimaz
Dipartimento di Chimica Fisica e Ambiente, Università degli Studi
Via Cotonificio 108, 33100 Udine, Italy
Phone: +39 0432 558731; fax: +39 0432 558700; e-mail: stefano.grimaz@uniud.it