Seismic early warning systems for the process industry

G. Fabbrocino,
Dipartimento S.A.V.A., Università del Molise, Campobasso, Italia

I. Iervolino, G. Manfredi
Dipartimento di Analisi e Progettazione Sismica, Università di Napoli "Federico II", Napoli, Italia

E. Salzano
Istituto di Ricerche sulla Combustione, CNR-IRC, Napoli, Italia

ABSTRACT: Early Warning System, i.e. a set of actions that can be taken from the moment when a seismic event is triggered with a significant reliability to the moment the quake strikes in a given location, seems to be a very valuable tool for the prevention of industrial damages. In the present paper, some insights for the process industry are presented. The aim is to discuss the main aspects related to management of large amounts of hazardous substances as well as to protection against failures and faults generated by seismic base excitations. Relations between structural monitoring, seismic reliability of equipments and industrial quantitative risk analyses will be analysed; critical issues will be discussed from an interdisciplinary standpoint in order to exploit the potentialities and define even limitations of the approach.

1 INTRODUCTION

Safety of industrial facilities and interaction between natural hazards and industrial risks are becoming a key issues in view of urbanised areas and environment protection. This circumstance is related to the development and the refinement of risk assessment procedures able to evaluate from a quantitative point of view the consequences of failures and/or faults of processes involving hazardous materials. With specific reference to earthquakes, the extension of areas exposed to seismic risk worldwide is leading the process industry to develop methodologies for the assessment of risk either in the early design of plants or for existing installations, to introduce acceptable risk criteria and thresholds values for earthquake intensity, and consequently to develop active and passive actions for the prevention and mitigation of accidental scenario triggered by earthquakes.

In this framework, Early Warning System (EWS) seems to be valuable tools. An EWS is a set of actions that can be taken from the moment when a seismic event is triggered with a significant reliability to the moment the quake strikes in a given location. As a result, prevention of damages via relevant countermeasures can be started. To this regard, it's worth noting that early warnings of earthquake are recognised as a focal point for the prevention of nuclear accidents, whereas few attention is given to the seismic safety management in the wider case of chemical processes where large inventories of hazardous chemicals are stored. Indeed, active protection system as safety interlock systems (SIS) are normally installed for the shut-off of plants for relatively fast, process-related loss of control, whereas the few seconds allowed typically by the seismic wave propagation to reach the installation location are rarely considered for mitigation of earthquake effects on plants, processes and storage systems.

Safety interlock systems (SIS), also defined emergency shutdown systems, are among the most important protective measurements in process plants, and provides automatic actions to correct an abnormal plant event that has not been controlled by basic control systems and manual interventions (CCPS, 1993; Green & Dowell, 1995). The design and maintenance of SIS present a special challenge created by the infrequent need for these systems to act; i.e., a SIS is only needed on those rare occasions when normal process controls are inadequate to keep the process within acceptable bounds (Chung et al., 2000). In the normal process-life, a SIS failure is likely to be followed by environmental damage or loss of human lives.

In this paper, the current authors propose a methodology to analyse the possibility to predict, prevent and mitigate earthquake damages, not only in terms of structural, mechanical damages but also in terms of loss of containment of hazardous materials from the containment system or, more simply, from the storage equipment. More specifically, a main issue is that only industrial accidents which are followed by the release of large amount of hazardous materials or energy into the surrounding environment will be considered (Lindell & Perry, 1996), i.e., our purposes is addressed to the mitigations of effect on human body due to toxic dispersion of vapour or gas substances, due to fire of liquid releases on the ground or the fire and explosion of flammable clouds formed after the dispersion of gas or vapour from the system of containment. In other words in what is called "relevant accident" (Council Directive 96/82/EC; COMAH, 1999). Also, some indications for the threshold limits for the earthquake intensity are given.

The main aspect of EWS to take into account for the development of mitigation actions for earthquake and its relation with process industry is the characteristic time for earthquake scenario to strike in a given location, which is now defined as τ_{EWS}, to be correlated to the characteristic time of EWS action on the process industry, τ_{Action}.

Our proposal is then related to the definition of a specific a-dimensional number, the Earthquake Process-industry early Warning number (EPW) which is the ratio of these two characteristic times.:

$$EPW = \alpha \frac{\tau_{EWS}}{\tau_{Action}} \qquad (1)$$

where α is a coefficient which depends on the earthquake intensity parameter and is discussed in the following.

The EPW number allows to address safety management to mitigation actions Quite clearly, the greater the EPW the stronger the possibility of preventing damages to plant installations and possibly mitigating the effects of earthquake, due to the longer available time of seismic wave arrival, due to the short time of intervention or even to the very low intensity of earthquake, which however depends on the equipment specificity.

Table 1 reports the ranges of EPW value which characterize the possibility and the effectiveness of earthquake mitigation action on the process plant, as proposed by the current authors.

From the words above, it's clear that the definition of both EPW characteristic times for a specific location is the key point of this analysis. Indeed, they are strongly dependent on location, type of process, and many – often – unpredictable figures. Large variation are then expected.

Finally, following the definition of EPW, it's likely that spurious shutdowns may result. In the following some indications for the threshold limits for the earthquake intensity are given.

Table 1: Early Warning System correlated by means of the EPW number, the type of action and the earthquake intensity.

EPW	***Type of action***	***Earthquake intensity***
0.0 – 1.0	The arrival time of earthquake is short and/or characteristic times for mitigation action are very long	The earthquake intensity does not affect the mitigation action
1	The arrival time of earthquake and mitigation action are comparable	The earthquake intensity affects the mitigation action if multiple catastrophic failure of containment systems and mitigation safety auxiliary systems (e.g. sprinkler systems) are affected
> 1	The arrival time of earthquake is long and/or the time needed for effective mitigation action is low	The earthquake intensity affects the mitigation action if multiple catastrophic failure of containment systems and mitigation safety auxiliary systems (e.g. sprinkler systems) are affected. However, several action prior to the arrival of earthquake are possible to avoid further catastrophic consequences
>> 1	The arrival time of earthquake is very long and/or the time needed for effective mitigation action is very low	Earthquakes and mitigation action are independent. Effective actions prior to the arrival of earthquake are possible

2 THE CHARACTERISTIC EWS TIME, τ_{WES}.

Early Warning Systems can determine location, origin time and magnitude of an earthquake based on the analysis of the energy content of the low amplitude P waves which generates ahead of time compared to the high amplitude S waves. Provided that both a network of properly operating sensors and a fast communication system are available, an EWS can forecast an earthquake from a few to some dozens seconds before its arrival at a selected location, up to about 90 seconds.

The interest of the current author is specifically addressed to the Neapolitan area, which is a very high seismic risk area, and it is subjected to earthquakes of volcanic and tectonic origin, that have the epicenter in the Appennino Range, at 70 km from the city. Hence, the seismic activity is monitored by the national seismic network of Istituto Nazionale di Geofisica e Vulcanologia (INGV). The seismic network is improving and at the same time a seismic/accelerometric network for the Irpinia zone is being implemented by the Regional Center of Competence on Analysis and Monitoring of Environmental Risk (CRdC-AMRA) (Gasparini et al., 2003).

Clearly, the knowledge of EPW number can address the location of network system in terms of distance from the process industry, by knowing the characteristic velocity of propagation in the soil of seismic wave.

3 THE CHARACTERISTIC TIME FOR ACTION, τ_{action} .

The time for action after earthquake alarm depends on many factor and it's clearly dependent on the type of process considered. Indeed, quite obviously, each process has its own peculiarity and general assumption are often not applicable. However, some insight may be given if different, general classes of processes involving high amounts of flammable or toxic substances may be sketched: i) liquid fuel storage or large-scale atmospheric equipment; ii) above-ground gas storage system; iii) under-ground gas reservoir, mounded or buried gas storage system and pipelines. As cited above, this list is not exhaustive as only some representative industrial equipment are considered. Moreover, often chemical processes are often composed by two or more classes.

In the following the time τ_A is defined for atmospheric storage plant category and pressurised above ground storage facility only. The methodology has been already assessed for liquid storage plant, whereas only preliminary analysis is given in this paper for pressurised equipment.

The entire procedure is extensible to any other process.

3.1 *Liquid fuel storage plant*

The current authors have produced recently a methodology for the earthquake hazard of liquid fuel storage plants (Salzano et al., 2004; Fabbrocino et al., 2005). The probability of failure and loss of containment with respect to the Peak Ground Acceleration (PGA) has been defined by means of simple statistical function. The assumption of PGA as the only intensity parameter for seismic intensity has been necessary in the light of simplification needed when complex risk assessment of industrial plants is performed.

In the case of liquid fuels, unless earthquake is so intense that the rapid catastrophic failure of one or more tanks is observed, the release of liquid after the failure is typically slow and mitigable.

With specific respect to the preventing and mitigation actions, the shutdown of operation should be directed essentially to the lock of operation of loading/unloading of fuels from/to tank truck or boat (by pipeline). In this case, the SIS consists of simple safety valves which almost instantaneously can section pipelines. Moreover, the transient phases and the possible release of fuel on the ground should be negligible and fires (explosions are very unlikely for many categories of fuel and the possible presence of early ignition of vapour cloud due to static energy) are only related to the presence of fuel in catch basin.

Eventually, the typical time of 30s and 10min as reported in the well known Yellow Book (Lees, 1996; Uijt de Haag, P.A.M. & Ale, B.J.M., 1999) respectively for the automatic and manual safety valve isolation should be considered.

If major loss of containment are of concern, mitigation interventions for the slow release are always possible in the catch basins from the failed tanks, whereas (often delayed) localized fires are likely. Foam can be sprayed over the catch surface prior the tank shaking and thus fires are avoided. The foaming action is of course difficult if the earthquake is so energetic that the entire foaming system has failed structurally. The time for foaming action to cover the basin surface surrounding the tank can be again considered within the 30 seconds as said above.

The factor α in the EPW number takes into account the earthquake intensity. To this regard, in previous papers (Salzano et al., 2003; Fabbrocino et al., 2005), we have defined the concept of limit states for the classification of equipment damage, following HAZUS damage classification (1997). A linguistic term DS has been referred to the mechanical damage, and the term RS has been used to define the loss of containment which derives from the DS level of damage to equipment. In the same papers, for the sole loss of containment RS state from storage tanks, the probability of occurrence of any limit state has been assessed by means of fragility curves, starting from a consistent data set describing the behaviour of tank loaded by earthquakes.

Here, extension of those analysis has been reported for both unanchored and anchored storage tank, at different fill level. The results has been then used for the statistical definition of minimum threshold values for PGA (PGA_k) for the mechanical damage and for the intensity of loss of containment, the latest being the main issue to take into account for emergency response. More specifically, the value of PGA corresponding to the zero probability of occurrence of risk state (DS=structural damage or RS=risk state for the loss of containment), has been obtained, for all risk state. Results and details are reported in the Table 2.

As observed in the table, storage tanks with fill level close to the full are the most sensitive to earthquake and can be used for conservative results on threshold values, even keeping into account the uncertainties in the level of tank at earthquake time.

Unless specific values are used for the analysis, the PGA_k = 0.120 g obtained for anchored storage tanks (typically designed in seismic areas) for the catastrophic loss of containment (RS = 3; DS > 4) can be considered for the effectiveness of EWS action. Indeed, greater values of PGA produce possibly multiple tank damage and time for intervention is strongly affected.

Table 2: PGA threshold value (PGA_k) for damage states DS and RS for atmospheric oil storage tanks subjected to earthquake.

RS	DS	Type of storage	Fill level	PGA_k [g]
RS = 1 Negligible loss of containment	DS=1 Negligible structural damages	Anchored	≥ 50%	< 0.395
			Near full	< 0.075
		Unanchored	≥ 50%	< 0.115
			Near full	< 0.045
RS=2 Considerable loss of containment	DS=1 Negligible structural damages	Anchored	≥ 50%	0.395
			Near full	0.075
		Unanchored	≥ 50%	0.115
			Near full	0.045
	DS=2 Low structural damage	Anchored	≥ 50%	0.370
			Near full	0.170
		Unanchored	≥ 50%	0.100
			Near full	0.770
RS=3 Total instantaneous loss of containment	DS=3 High structural damage	Anchored	≥ 50%	0.580
			Near full	0.120
		Unanchored	≥ 50%	0.165
			Near full	0.120
	DS=4 Catastrophic structural damage	Anchored	≥ 50%	0.660
			Near full	0.395
		Unanchored	≥ 50%	0.895
			Near full	0.070

The value of α can be considered as a function of PGA following, in first approximation, the fragility function. Hence:

$$\alpha = \begin{cases} \to \infty & PGA << 0.1g \\ \approx 1 & PGA \le PGA_k = 0.1g \\ -0.83\ \ln(2.5\ PGA) & 0.1g < PGA \le 0.39g \\ \to 0 & PGA \ge 0.4g \end{cases} \qquad (2)$$

The value of α = 0 for PGA values much greater than 0.4 g means that no intervention keeps the plant in a safe state as it exists a probability greater than zero for total damage of the entire process plant, including auxiliary system and fire system. To this regard, PGA threshold value for buried pipelines as those typically used in the fire system installations should be considered as reference.

On the contrary, very high values of α means very high EPW number, i.e. a no damaging earthquake as PGA is too low. The α value is asymptotically the infinite for PGA = 0 and reach the value of unity around 0.1 g, where the prevention and mitigation action is only related only to the process safety action, if any damage to equipment. Simple function as $f(\alpha) = 0.1\ PGA^{-1}$ can be used.

In the range between 0.1 g and 0.4 g, the possibility of having damages is high: the function for alpha has been built by considering a logarithmic dependence of damage with the PGA.

Figure 1 reports the proposed plot for the function f(a) to be used in the following for the calculation of EPW number with specific reference to atmospheric storage tank.

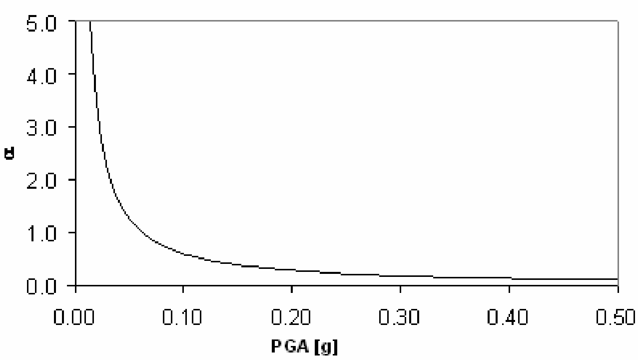

Figure 1. Proposed values for α as a function of PGA (g).

Figs. 2-3 report the EPW number by using the methodology proposed, and considering an automatic safety valve operating in a relatively very short time (30 s) and a manual, long operating time safety valve (10 min), which is closed after the earthquake alarm. The results are parametrical with respect to earthquake arrival time, expressed in seconds, in the range between 1 s and 60 s. Near full anchored atmospheric tank is considered for reference.

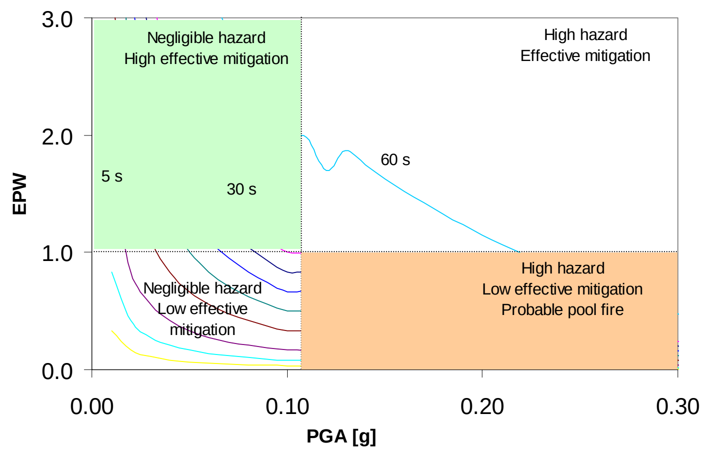

Figure 2. Calculated EPW for automatic safety valve by varying earthquake intensity expressed in PGA (g) and time of arrival of seismic wave (ranging from 1 s to 60 s) to the installation location. Near full anchored storage tank is considered.

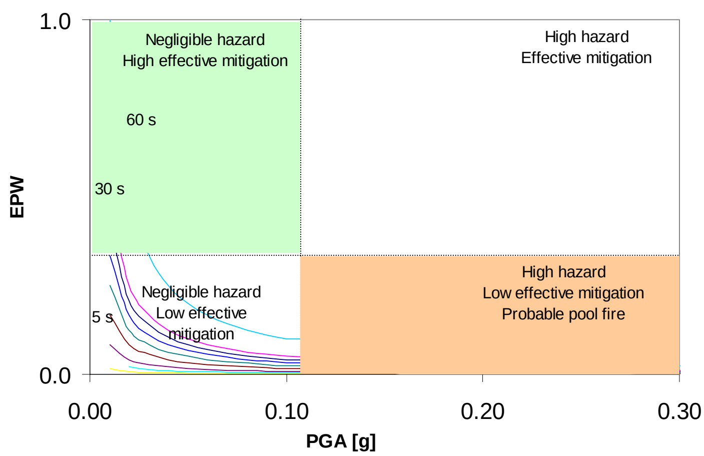

Figure 3. Calculated EPW for manual safety valve by varying earthquake intensity expressed in PGA (g) and time of arrival

of seismic wave (ranging from 1 s to 30 s) to the installation location. Near full anchored storage tank is considered.

Results show that when manual valves operate, process safety is only related to the intensity of earthquake. Indeed, EPW is positive only for low intensity earthquakes with low PGA values . On the other hand, when automatic operation is provided, even very destructive earthquake are possibly mitigable by emergency system.

The loss of containment is not directly linked with an escalation of accidents because ignition, for instance, is necessary for the pool fire to occur. Moreover, the benefit of mitigation action even for delayed fires (as the deluge system for adjacent tanks, if still working) may benefit. Quantitative risk analysis is then necessary for the safety management in order to identify global risks for the storage plant and for the preliminary comparison of possible seismic actions.

3.2 *Above-ground gas storage system*

When highly dangerous equipment are of concern, the leaflet of HSE (2005) is quite useful as a hierarchy of action should be analyzed, starting from the simple abandon of the plant to the isolation of pipelines and auxiliary system (e.g. pumping system) or both, and to the avoidance of escalation between adjacent vessels. Remotely automatic shut-off valves are mandatory for the velocity of action and for the necessity of avoiding the hazard of either toxic and/or flammable gases or vapors released from the system of containment. In the case of ground shaking able to produce structural damage to the systems, even of low intensity, considering as instantaneous the shutoff action, the time to be analyzed is referred essentially to i) the escape of personnel; ii) the limitation of escalation probability for the interaction of fires (mainly jet fire as the ignition probability is very high when earthquakes occur).

In the case of abandon of installation, toxic substances should be considered separately with respect to flammable materials. In the first case, water curtain are often necessary and the preferential way of escape should be described. The time for escape is simply proportional to the length of the safe path L_p to a safe area (e.g. control room) and to the average human velocity of escape. The latest ranges from 5 ms^{-1} (De Pinna, 1998) to 0.2 ms^{-1} and 0.5 ms^{-1} in the case of smoke conditions (Wright et al., 2005).

Earthquake early warning system should trigger the mitigation action for the possibility of escalation if other above-ground system are present, e.g. water deluge, aiming at cooling the walls. Emergency emptying of vessel to a safe area or equipment (e.g. scrubber systems or to emergency discharge to torch) could be also considered in the case of very toxic substances.

Analysis of PGA threshold values (PGA_k) for damage states DS (structural damage) and RS (loss of containment) for pressurized equipment is still missing. Quite clearly, the effect of earthquakes should be by far more intense in terms of PGA for having structural damage. A preliminary analysis has showed a value of 1 g as the minimum PGA for some damage to the shell and pipelines of pressurised on-ground equipment.

On the contrary, no words can be said with respect to the loss of containment, as even low damages may result in crack of shell with the rapid flow of containment to the external environment or in some cases within buildings (e.g. ammonia cooling equipment).

Explosion and flash fire (see Lees, 1996 for details on accidental scenarios after earthquake actions) are always possible when large structural damage occurs.

4 CONCLUSIONS

The earthquake shutdown logic discussed in this paper is addressed to the minimization the consequences of hazardous release. To this aim, designers and managers of chemical manifacturing and onshore oil processing operations often adopt simple isolation of inventories (HSE, 2005), for instance by closing valves, either manually (remotely operated or automatic) or removing power from motors, whereas a number of active and passive actions may represent appropriate tools to bring process plant in safe state after earthquake warning.

An a-dimensional number for early warning system has been adopted and applied for atmospheric liquid storage plants. Other processes and equipment are still under observation. However, when underground gas reservoir or mounded /buried gas vessels are of concern, no escalation is likely and only shutdown of pipelines is necessary.

Finally, spurious shutdowns may have safety and economic implications because they lead to more dangerous operation as shutdown and start-up of industrial installations. These effects should be then considered for further investigations.

5 REFERENCES

CCPS, Center for Chemical Process Safety. 1993. *Guidelines for Safe Automation of Chemical Processes*. American Institute of Chemical Engineers, New York.

COMAH. 1999 *Control of Major Accident Hazards Regulations*, UK.

Council Directive 96/82/EC. 1996. On the control of major-accident hazards involving dangerous substances.

Fabbrocino, G., Iervolino, I., Orlando, F., Salzano, E. 2005. Quantitative risk analysis of oil storage facilities in seismic areas, *Journal of Hazardous Materials*, in press.

Gasparini, P., Barberi, F., Belli, A. 2003. Early Warning of Volcanic eruptions and Earthquakes in the neapolitan area, Campania Region, South Italy. *Proceedings of the International IDNDR-Conference on Early Warning Systems for the Reduction of Natural Disasters*, Bonn, Oct. 16-19.

Green, D.L. & Dowell, A.M. 1995. How to design, verify and validate emergency shutdown systems, *ISA Transactions*, 34, 261-272.

HAZUS (1997). *Earthquake Loss Estimation Methodology*, National Institute of Building Sciences, prepared by Risk Management Solutions, Menlo Park, California, (USA).

Health and Safety Executive. 2005. *Emergency isolation of process plant in the process industry - Chemical Sheet No 2*.

Lees, F.P. 1996. *Loss prevention in the process industries*, Butterworth Heinemann.

Lindell, M.K. & Perry, R.W. 1996. Identifying and managing conjoint threats: Earthquake-induced hazardous materials releases in the US, *Journal of Hazardous Materials*, 50, 31-46.

Salzano, E., Iervolino, I., Fabbrocino, G. 2003. Seismic risk of atmospheric storage tanks in the framework of quantitative risk analysis, *Journal of Loss Prevention in the Process Industry*, 16, 403-409.

Uijt de Haag, P.A.M. & Ale, B.J.M. 1999. *Guidelines for Quantitative Risk Assessment (Purple Book)*, Committee for the Prevention of Disasters, The Hague.

De Pinna, S. 1998. *Forces and Motion,* Austin, Texas: Raintree Steck-Vaughn Publishers,.

Wright, M.S., Cook, G.K., Webber, G.M.B. 2001. The effects of smoke on people's walking speeds using overhead lighting and wayguidance provision, *Proceedings of the 2nd int. conference on Human Behaviour in Fires*.