Journal of Hazardous Materials A123 (2005) 61–69

Journal of Hazardous Materials

www.elsevier.com/locate/jhazmat

Quantitative risk analysis of oil storage facilities in seismic areas

Giovanni Fabbrocino [a], Iunio Iervolino [a], Francesca Orlando [b], Ernesto Salzano [c,*]

[a] *Dipartimento di Analisi e Progettazione Strutturale, Università di Napoli "Federico II", Via Claudio 21, Napoli 80125, Italy*
[b] *Dipartimento di Ingegneria Chimica, Università di Napoli "Federico II", P.le Tecchio 80, Napoli 80125, Italy*
[c] *Istituto di Ricerche sulla Combustione, Consiglio Nazionale delle Ricerche, Via Diocleziano 328, Napoli 80124, Italy*

Received 22 October 2004; received in revised form 23 April 2005; accepted 25 April 2005
Available online 23 May 2005

Abstract

Quantitative risk analysis (QRA) of industrial facilities has to take into account multiple hazards threatening critical equipment. Nevertheless, engineering procedures able to evaluate quantitatively the effect of seismic action are not well established. Indeed, relevant industrial accidents may be triggered by loss of containment following ground shaking or other relevant natural hazards, either directly or through cascade effects ('domino effects').

The issue of integrating structural seismic risk into quantitative probabilistic seismic risk analysis (QpsRA) is addressed in this paper by a representative study case regarding an oil storage plant with a number of atmospheric steel tanks containing flammable substances. Empirical seismic fragility curves and probit functions, properly defined both for building-like and non building-like industrial components, have been crossed with outcomes of probabilistic seismic hazard analysis (PSHA) for a test site located in south Italy. Once the seismic failure probabilities have been quantified, consequence analysis has been performed for those events which may be triggered by the loss of containment following seismic action. Results are combined by means of a specific developed code in terms of local risk contour plots, i.e. the contour line for the probability of fatal injures at any point (x, y) in the analysed area. Finally, a comparison with QRA obtained by considering only process-related top events is reported for reference.

Keywords: Earthquake; Seismic risk; Industrial risk; Quantitative risk analysis; Multi-hazard

1. Introduction

Large part of European territory is affected by significant seismic hazard. On the other hand, industrial installations require mandatory risk assessment and development of preventive and protective actions [1]. Nevertheless, when industrial facilities and in particular chemical, petrochemical and oil processing industries are concerned, interaction of the earthquake with equipment may trigger relevant accidents resulting in release of hazardous materials (fires, explosions), injuring people and increasing the overall damage to nearby area, either directly or through cascade effects ('domino effects').

As a consequence, quantitative risk analysis (QRA) of industrial facilities has to take properly account of multiple hazards threatening critical equipments, which can possibly lead to catastrophic accidents.

Despite these considerations, engineering procedures to evaluate quantitatively the effects of seismic action on equipment are not well established, even if a large research effort has been undertaken to develop effective and sustainable, at least from a computational viewpoint, seismic reliability procedures [2] and qualitative aspects of the relationship between natural and technological disaster have been recently analysed by joint activities by European Commission DG Joint Research Centre, Institute for the Protection and Security of the Citizen (DG JRC) and United Nations International Strategy for Disaster Reduction (ISDR) [3].

In this paper, empirical seismic fragility curves and probit functions defined for both building-like and non building-like industrial equipment, have been crossed with outcomes of probabilistic seismic hazard analysis for a test site located

* Corresponding author. Tel.: +39 081 7621922; fax: +39 081 7622915.
E-mail address: salzano@irc.cnr.it (E. Salzano).

0304-3894/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhazmat.2005.04.015

in south Italy. Once the seismic failure probabilities have been quantified, consequence analysis has been performed for those events which may be triggered by the loss of containment following seismic action. Results have been then combined by means of a specific developed code in terms of local risk contour plots, i.e. the probability of fatal injures at any point (x, y) in the analysed area. In order to better point out the role of seismic hazard in industrial risk, the sole earthquake is then first assumed as triggering event. Hence, purely process-related "top events" are first excluded. A comparison with classical process-related quantitative risk analysis outcomes is then reported for reference, in order to show the relevance of seismic effects on risk indexes.

2. Seismic risk analysis of industrial components

Quantitative probabilistic seismic risk analysis (QpsRA) requires the evaluation of collapse probability of critical components and, subsequently, the analysis of phenomena triggered by loss of hazardous materials.

On the structural side, convolution of site's seismic hazard and vulnerability of each component leads to the collapse probability P_f (*failure probability*), which is the probability of the seismic capacity C being exceeded by the seismic demand D, integrated over all the possible values of the ground motion intensity measure (IM) (i.e. peak ground acceleration or PGA) [4].

$$P_\mathrm{f} = \int_0^\infty \mathrm{d}\,(\Pr[D > C]) = \int_0^\infty [1 - F_\mathrm{D}(u)]\, f_\mathrm{C}(u)\,\mathrm{d}u \qquad (1)$$

In Eq. (1), F_D is the cumulative probability distribution of the seismic performance *demand* for a given ground motion intensity, and f_C is the probabilistic density function of the seismic *capacity* of the structure/component. More explicitly, by probability algebra: the event of collapsing due to seismic action may be represented as the union of mutually exclusive events each of those representing component's collapse when a given level of seismic intensity occurs.

$$\mathrm{Collapse} = \bigcup_{i=1}^{\infty} \{\mathrm{Collapse} \cap \mathrm{IM}_i\} \qquad (2)$$

Events in Eq. (2) are mutually exclusive since collapse cannot take place for a given $\mathrm{IM} = \mathrm{IM}_i$ if another value already has led the system to failure, therefore failure probability is given by the sum of the probabilities of the elementary events defined. In other terms, by total probability theorem, P_f is given by the probability of the system failing for all possible values of seismic intensity (IM) combined with the probability of the latter occurring, therefore one can write:

$$P_\mathrm{f} = \sum_{\mathrm{All\,im}^*} P\left\lfloor D > C|\mathrm{IM} = \mathrm{im}^*\right\rfloor P\left\lfloor \mathrm{IM} = \mathrm{im}^*\right\rfloor \qquad (3)$$

Finally, structural seismic risk is the convolution of $P[D > C|\mathrm{IM} = \mathrm{im}^*]$ (commonly referred as *fragility curve*, function of im*) and $P[\mathrm{IM} = \mathrm{im}^*]$ which is the *seismic hazard curve*, the outcome of probabilistic seismic hazard analysis [5,6].

Here it is worth noticing that the structural failure $P[C > D|\mathrm{IM}]$ in Eq. (3) does not depend on other earthquake characteristic such as magnitude or source-to-site distance, as this happens when IM is "sufficient", e.g. has a exhaustive explanatory power on the structural response. The topic of sufficient intensity measures for seismic risk assessment of structures is wide and is detailed elsewhere. For reviews, see [7,8].

According to this procedure, seismic risk has been carried out for all structures in the plant, therefore seismic hazard analysis has been required to get the occurrence probability $P[\mathrm{IM} = \mathrm{im}^*]$ in terms of the same intensity measure used to describe the seismic vulnerability of the component in question. Peak ground acceleration (PGA) has been considered as the ground motion intensity measure (IM) due to the nature of the damage database used. Further details may be found elsewhere [9]. In the following sub-sections, probabilistic seismic hazard analysis and vulnerability review are presented.

2.1. Seismic hazard

Measured ground motions refer to seismic waves radiating from the earthquake focus to the site and can be related to three types of mechanisms that interact to generate the actual signal: *source*, *path* and *site*. Efficient ground motion intensity measures for engineering applications should be strongly correlated with structural seismic response. These parameters summarize all the random features of earthquakes, including energy, frequency contents, phases and others which may affect the structural response of structures. Currently, the problem of definition of good predictors for inelastic seismic behaviour of structures is one of the main topics of earthquake engineering. However, empirical vulnerability analyses are often carried out in terms of peak ground acceleration, mainly because it is relatively easy to infer (i.e. by earthquake intensity conversion) while others intensity measures (as first-mode spectral acceleration) may not be available at the site for post-earthquake damage observation.

Probabilistic seismic hazard analysis is represented by Eq. (4) where the integral, computed for each possible realization (pga*) of PGA gives a point of the hazard curve. For the study case discussed herein PSHA has been then carried out by a specifically developed code [10], referring to the Sabetta and Pugliese [11] ground motion attenuation relationship, for the site of Altavilla Irpinia (AV—southern Italy) where the plant is assumed to be located (Fig. 2).

$$P[\mathrm{PGA} > \mathrm{pga}^*] = \iiint_{m,r,\varepsilon} P\,[\mathrm{PGA} > \mathrm{pga}^*|M = m,\, R = r,\, E = \varepsilon] \times f_{M,R,E}(m, r, \varepsilon)\,\mathrm{d}m\,\mathrm{d}r\,\mathrm{d}\varepsilon \qquad (4)$$