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# The Inclusion of Natural Hazards in QRA: the Seismic Event

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QRA procedures applied to industrial equipment require special attention when dealing with unconventional hazard scenarios. In this perspective, the role played by severe natural events on the functionality of an industrial system is surely of interest in any exhaustive risk assessment study.
The focus on earthquake initiating events is due to their severity and strong destructive potential that can lead to severe damages, domino effects and cross effects on residential and industrial sites.
In this work, a probability approach that includes unconventional initiating events in usual Fault Tree and Event Tree analysis procedures is proposed to ensure a reliable earthquake-related event management. Main relevant parameters are evaluated, in addition to the typical expected structural behaviour of the industrial structure. The comparison between the scenario without the seismic event and that aggravated by the earthquake shows that, depending on the both the seism and structural parameters, such an unconventional initiating event worsen the final outcomes. Variations are depending on the site-epicentre distance and the seism magnitude and peculiar effects on the final outcomes are observed both in the FTA and ETA initiating branches.

## 1. Introduction

Critical civil and industrial structures are essential in the growth economic prospects. These facilities like public management buildings, public forces, command centres, water and power supply, O&G pipelines; chemical plants, etc., show criticality that is mainly due to their role in the developed society. Linked activities, in addition, cannot suffer outages being linked to a continuous operation of such strategic operations.
Among these, industrial facilities can suffer severe hazard scenarios resulting from defects, intrinsic and extrinsic hazards of processed substances, control failures and SMS gaps (Wada et al., 2013). So many causes can lead to industrial accidents but recently many studies have focused on large scenarios induced by natural events (Natech). In this perspective, decisive causes are represented by earthquakes, lightning, flood and tsunami and belong to so-called non-conventional initiating events (Antonioni et al., 2007).
Safety predictive and preventive studies require the exact knowledge of these initiating events and the cascading roots to final events, leading to an industrial accident. However, while conventional causes are already robustly incorporated in QRA procedures, non-conventional initiating events suffer a lack of structured incorporation methods and are usually neglected in qualitative and quantitative safety studies (Sipos and Hadzima-Nyarko, 2017).
The occurrence of the seismic event can be included in the *HazId* (Hazard Identification) procedure and the quantitative analysis, in addition to conventional accidental causes. It should be noted, however, that this initiating event exhibits peculiar implications:

- severe and extensive damages over large areas (industrial, residential, …);
- delay in rescue operations, induced by a general discontinuation in routes and communications;
- enhanced devastation with domino effects.

The resulting scenario is very sensitive to the earthquake parameters (magnitude, PGA, PGV, soil typology) and the vulnerability of industrial structures (Babic and Dolsek, 2016). Being the earthquake a statistically rare event, a suitable probabilistic approach is required as well as a proper equipment response mode to the

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seismic action. This work focuses on the application of the Fault Tree and Event Tree Analysis to a LOC (Loss of Containment) scenario induced and escalated by an earthquake event. Conventional failure causes are thus supplemented with effects related to the seismic action and the proposed methodology of Section 2 and 3 is applied to a representative tank of flammable materials.

## 2. Description and modelling of the earthquake initiating event

### 2.1 The modelling of the seismic source

The earthquake properties are defined by means of a set of parameters that are specifically representative of the local soil effects induced by a seismic source. The most representative are the magnitude $m$, the local peak ground acceleration $PGA$ and the local peak ground velocity $PGV$. These parameters are usually employed in the definition of expected damages and to drive the seismic retrofitting.
However, once the seismic event is included as an initiating cause to industrial accidents, an earthquake recurrence model is also required. This approach treats the seismic source probabilistically, providing a measure of the expected frequency of occurrence $\Omega$ of a specified earthquake with $m > \widetilde{m}$ (PSHA – Probabilistic Seismic Hazard Assessment). The general formulation is reported in Eq. 1:

$$\log_{10} \Omega = a - b\widetilde{m} \tag{1}$$

$\widetilde{m}$ is intended as the threshold reference magnitude value, $a$ and $b$ are instead linked to the seismic activity in the study area (Gutenberg and Richter, …).
It is assumed that a Poisson distribution of rare events is representative of induced earthquakes and thus a probability specification $P$ is derived as of Eq. 2:

$$P(m > \widetilde{m}) = \frac{(t\Omega)^n e^{-t\Omega}}{n!} \tag{2}$$

In eq. 2, $t$ is a proper lifespan that is indicative of the normal average lifetime expected for an industrial equipment (50 yr) and $n$ is the number of observed events with $m > \widetilde{m}$. The related exceedance likelihood $P_e$ is reported in Eq. 3:

$$P_e(m > \widetilde{m}) = 1 - e^{-t\Omega} \tag{3}$$

The modelling of the soil recorded parameter ($PGA$, $PGV$) relies on the ground motion prediction equation (GMPE) that is linked to the earthquake magnitude $m$, source-site distance $d$, class of the site $\gamma$ and fault typology $\varphi$. Each relevant ground parameter $\Gamma$ is assumed to follow and exponentially-shaped function (Eq. 4):

$$\Gamma = \exp[f(m) \cdot f(d) \cdot f(\gamma) \cdot f(\varphi)] \tag{4}$$

As suggested by Bommer et al. (Bommer et al., 2010a), in this approach the probability of exceedance is straightforwardly derived from the GMPE and is normally distributed. In this work, a specific GMPE for the Italian area is used (Akkar and Bommer, 2010).

### 2.2 Description of the impulsive seismic effect on the industrial structures

The seismic effect on the industrial equipment is based on a threshold analysis of the natural period of vibration $T_{nat}$. This property is derived from the characteristic shape of the equipment considered, its mass and the inertial momentum and the effect of the seism is accepted once the locally induced vibration period $T$ exceeds $T_{nat}$. The locally expected vibration period $T$ is estimated from the spectral acceleration resulting from the seismic event.
This methodology is applied to a representative industrial tank as of Fig. 1. The structural analysis allows for the estimation of the reference natural period of vibration $T_{nat}$ (Eq. 5, ASCE 2011):

$$T_{nat} = \sqrt{\frac{\sum(w \cdot \Delta\alpha) + H^{-1}\sum(W \cdot \beta)}{\sum(E \cdot D^3)\, t\Delta\tau}} \tag{5}$$

In Eq. 5, $C[-]$ is a structure-related coefficient (impulsive period of vibration), $H\ [ft]$ and $D[ft]$ are respectively the overall height of the tank and the diameter of each structural section, while $w[lbs/ft]$ is representative of the distributed weight of each structural section and $(\alpha, \beta, \tau)$ is a set of coefficients linked to the tank filling level.

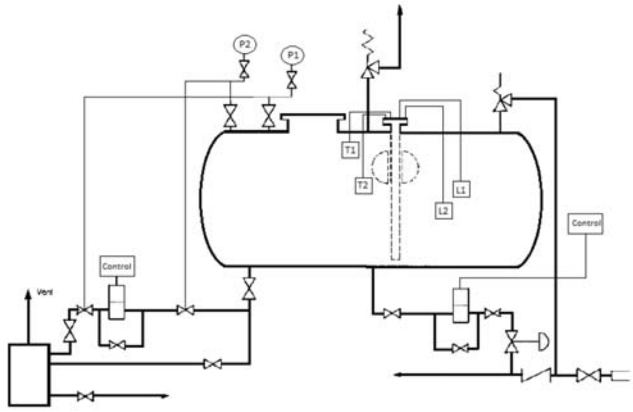


*Figure 1: Benchmark industrial tank, general scheme (Lees, 1996).*

## 3. Quantitative risk assessment: the inclusion of the seismic initiating event.

The seismic event was included in the usual Quantitative Risk Assessment (QRA) procedure as an initiating event for the final considered outcome. As part of future developments, the Top Event considered is linked to an unintentional LOC (loss of containment) from the tank.

In this study, both conventional and unconventional causes are considered and arranged in a Fault Tree Analysis (FTA) and the seismic event is regarded as a primary undeveloped failure. It is supposed that the seismic event may influence the LOC event because of its activity on the tank collapse and the connection failure in the inlet/outlet piping (disconnections).

The FTA thus includes the following initiating chains to the LOC Top Event:

- tank rupture, internal over-pressuring scenario induced by intermediate events linked to sensors failures and faults of the safety equipment (pressure relief valve, rupture disk);
- tank rupture, internal over-pressuring scenario induced by a failure in the cooling jacket and an increase in the internal tank temperature;
- tank rupture, seismic induced scenario.

These branches probabilistically contribute to the Top Event and are arranged, along with intermediate and primary events, in the Fault Tree.

The earthquake phenomenon is also intended as cause of discontinuations in the mitigative barriers and equipment. As a preliminary target, it is assumed that this natural event may affect the containment barrier structural integrity and may damage the sprinkler fire-fighting system. Further investigations will supplement the Event Tree Analysis (ETA) with the quantification of variations in the immediate and delayed ignitions related to the earthquake impact.

## 4. Results and discussion.

Two distinct scenarios are considered, namely without (conventional) and with (unconventional) the earthquake as a basic initiating event. For each incidental chain, different FTA and ETA are performed to highlight the earthquake incidence on the statistical occurrences.

Tank and substance specifications are reported in Table 1. The equipment shape and conformation agree with API standard 620.

*Table 1: Tank specifications (API, 2013).*

| | Ext. diameter, m | Tot. height, m | Int. volume, $m^3$ | Material | Containment |
|---|---|---|---|---|---|
| Tank 1 | 2.50 | 4.52 | 20 | SS 304 | *n*-$C_5$ |
| Tank 2 | 1.80 | 4.75 | 9 | SS 304 | Methyl acetate |

Earthquake parameters are listed in Table 2.

*Table 2: Earthquake parameters.*

| Magnitude | GMPE | Site factors | Spectral ordinates, $m/s^2$ | Epicentre-site distance, km |
|---|---|---|---|---|
| 5.5 and 7 | Akkar and Bommer (2010), Italy | SS (1)<br>S1 (1.3) | 1.31g<br>0.55g | 20<br>50 |

**4.1 Basic scenario, no earthquake.**

The earthquake occurrence is neglected and reported probabilities are only due to conventional mechanical and instrumentation failures; no epicentre-site distance distinctions are specified.
FTA probability outcomes in a 50-yr period are listed in Table 3.

*Table 3: FTA outcomes, probabilities in 50-yr time period.*

| Event | Probability, - |
|---|---|
| **Tank 1 and 2** | |
| General inlet valve system failure | 0.020 |
| General outlet and safety valve system failure | 0.024 |
| Inlet piping failure | 1.15e-4 |
| Outlet piping failure | 1.15e-4 |
| Tank failure | 0.090 |
| LOC (Top Event) | 0.380 |

The LOC occurrence probability amounts to 0.380 with the main contribution given by a mechanical tank failure. No differences are expected in the piping failure being inlet and outlet systems almost comparable in terms of materials, operative conditions and relevant parameters.
Resulting success rates from the ETA are reported in Table 4 (Mannan, 2005).

*Table 4: ETA outcomes, success rate in 50-yr time period.*

| Event | Success rate, events/50 yr | Occurrence rate, events/50 yr |
|---|---|---|
| **Tank 1 and 2** | | |
| Immediate ignition | 0.05 | |
| Delayed ignition | 0.18 | |
| Sprinkler intervention on demand | 0.88 | |
| Explosive range occurrence | 0.16 | |
| Containment barrier | 0.50 | |
| Uncontrolled LOC (Top Event) | | 0.48 |

Table 4 lists success rates in 50 yr of expected mitigation measures and FTA Top Event evolution. Ignitions (immediate and delayed) are invoked given the flammable properties of both $n$-$C_5$ and methyl acetate, as well as the potential explosive conditions.

**4.2 Unconventional scenario, with earthquake occurrence.**

The unconventional scenario is derived from the basic FTA-ETA scheme of section 4.1 and requires the inclusion of the earthquake initiating cause (Table 2) in the incidental chain. Once the seismic scenario is included, resulting probabilities vary given the additional contribution to the Top Event due to induced failures. Tank 1 and 2 results are reported in Table 5 and 6.
As expected, the comparison among Table 5-6 (unconventional scenario) and 3 (conventional scenario) shows that the seismic event induces a generalized increase in the occurrence probabilities. Main variations are observed with respect to tank and piping failure scenarios that are more sensitive to induced seismic vibrations. Increasing the earthquake magnitude, these intermediate scenarios are more likely given their susceptibility to the seismic action. At 5.5 magnitude (not reported), no relevant differences are detected with the base case being the magnitude not strong enough to severely affect the equipment structural integrity at 20 and 50 km. It should be observed that the investigated earthquake, with no seismic retrofitting, increases the Top Event probability from 0.38 to more than 0.90 if the target is located within 20 km from the epicentre.
On this basis, the LOC event is expected 1.84 occurrences/50 yr at 20 km and 0.53 occurrences/50 yr at 50 km with resulting MTBF respectively of 27 and 94 yr. Different outcomes are experienced by Tank 2 with shorter MTBF and higher occurrence probabilities.

*Table 5: Tank 1. FTA outcomes with 6.0 earthquake, probabilities in 50-yr time period.*

| Event | Probability, - | |
|---|---|---|
| | **Magnitude 6.0, 20 km** | **Magnitude 6.0, 50 km** |
| General inlet valve system failure | 0.185 | 0.110 |
| General outlet and safety valve system failure | 0.190 | 0.110 |
| Inlet piping failure | 0.090 | 0.006 |
| Outlet piping failure | 0.090 | 0.006 |
| Tank failure | 0.270 | 0.190 |
| LOC (Top Event) | 0.830 | 0.420 |

*Table 6: Tank 2. FTA outcomes with 6.0 earthquake, probabilities in 50-yr time period.*

| Event | Probability, - | |
|---|---|---|
| | **Magnitude 6.0, 20 km** | **Magnitude 6.0, 50 km** |
| General inlet valve system failure | 0.210 | 0.120 |
| General outlet and safety valve system failure | 0.214 | 0.121 |
| Inlet piping failure | 0.110 | 0.020 |
| Outlet piping failure | 0.112 | 0.020 |
| Tank failure | 0.290 | 0.201 |
| LOC (Top Event) | 0.930 | 0.480 |

Differences arise from the individual seismic behaviour of analysed tanks according to their shape, size and content that results in different natural vibration periods and thus in the seismic susceptibility. Tank 2 exhibits a lower natural vibration period and the earthquake response is generally more severe.

For the same reason, a variation in the filling degree of the tanks determines the seismic behaviour although results show that this parameter has a limited effect, especially when large part of the total mass is given by the tank structure. A key role, instead, is played in *sloshing* mechanisms that are neglected in this preliminary assessment. Further studies are in progress on this topic.

The seism alters the Top Event evolution to final outcomes (Table 7). ETA analysis results show that this unconventional initiating event may influence also the reliability of mitigation measures. In this study, the effects on the firefighting systems and physical containment barriers are investigated. Basic rates are reported in Table 4, the earthquake effect is not included. Main results of the seismic event include structural damage to the containment barrier and sprinkler system outages (disconnections, damages, supply discontinuation).

Data rates are based on Mannan, 2005 and results are reported in Table 7 and 8.

Final outcomes are sensitive to the earthquake magnitude and the distance from the epicentre. Success rates related to the containment barrier and firefighting system are reduced as result of the seismic action that basically affects the failure rate.

As expected, more severe earthquakes and a reduction in the epicentre distance act as aggravating criteria thus propagating the Top Event occurrence rate that increases from 0.48 occurrences/50 yr (conventional scenario) to more than 2.6 occurrences/50 yr. In this sense, the seismic initiating event is responsible for an increase in the basic occurrence rate of the *Top Event* of more than four times with a severe escalation of the accident effects.

*Table 7: ETA outcomes with 6.0 magnitude earthquake, success rate in 50-yr time period. Tank 1.*

| Event | Success rate, events/50 yr | |
|---|---|---|
| **Tank 1** | **Magnitude 6.0, 20 km** | **Magnitude 6.0, 50 km** |
| Immediate ignition | 0.050 | 0.050 |
| Delayed ignition | 0.180 | 0.180 |
| Sprinkler intervention on demand | 0.789 | 0.874 |
| Explosive range occurrence | 0.160 | 0.160 |
| Containment barrier | 0.409 | 0.494 |
| | Occurrence rate, events/50 yr | |
| Uncontrolled LOC (*Top Event*) | 1.840 | 0.530 |

*Table 8: ETA outcomes with 6.0 magnitude earthquake, success rate in 50-yr time period. Tank 2.*

| Event | Success rate, events/50 yr | |
|---|---|---|
| **Tank 2** | **Magnitude 6.0, 20 km** | **Magnitude 6.0, 50 km** |
| Immediate ignition | 0.050 | 0.050 |
| Delayed ignition | 0.180 | 0.180 |
| Sprinkler intervention on demand | 0.770 | 0.860 |
| Explosive range occurrence | 0.160 | 0.160 |
| Containment barrier | 0.390 | 0.480 |
| | Occurrence rate, events/50 yr | |
| Uncontrolled LOC (*Top Event*) | 2.660 | 0.650 |

## 5. Conclusions

Accidental scenarios induced by a seismic action may result in severe consequences with extended damages and equipment failures.

This work focused on the qualitative and quantitative inclusion of the seismic effect on usual QRA procedures used for risk assessment purposes. The earthquake scenario, intended as unconventional primary inducing event was inserted in the Fault Tree and Event Tree analysis, in addition to conventional failure causes.

A proper approach, comprehensive of earthquake recurrence modelling and its effects on typical industrial facilities, is developed in order to give a quantification of relevant risk assessment parameters.

The method is applied to a representative industrial storage tank filled with flammable liquids. Two tanks, with different size and shape, are analysed in terms of behaviour under different earthquakes scenarios.

Results show that unconventional initiating events can be successfully included both in the FTA and ETA.

On this perspective, the seismic event leads to a generalized decrease in the MTBF of the Top Event (loss of containment), mainly driven by enhanced tank and auxiliary equipment failures. More severe earthquakes and a reduction in the site – epicenter distance raise the Top Event probability occurrences, that can be increased up to four times. In addition, the LOC event is worsened by damaging effects on the mitigation systems induced by the earthquake that may endanger both containment barriers and firefighting equipages.

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