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Sensitivity Analysis of a Short-Cut Methodology for Assessing Earthquake-Related Na-Tech Risk

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Natural disasters may be powerful and prominent mechanisms of direct or indirect release of hazardous material (hazmat) (Young et al., 2004). If industrial sites are located in naturally hazard-prone areas, technological accidents may be triggered by natural events, such as storms, earthquakes, flooding, and lightning, generating the so-called Na-Tech (Natural and Technological) events and may modify as well as increase the impact and overall damage in surrounding areas (Galderisi et al., 2008). There is a wide range of literature on natural disasters and hazardous material accidents, but it is only in recent years that they have been treated as related events. Thus, Na-Tech events have begun to receive a significant amount of attention. Additionally, natural disasters have increased both in frequency and economic losses around the world (Young et al., 2004); therefore, there is increasing public awareness and interest from the scientific community.
A qualitative methodology for the initial assessment of earthquake-related Na-Tech risk, where the full details of the method used in this work are discussed, (Busini et al., 2011) was developed as a screening tool to identify which situations require a much more expensive Quantitative Risk Analysis (QRA). The methodology, through suitable Key Hazard Indicators (KHIs), identifies the Na-Tech risk level associated with a given situation (i.e., a process plant located in a given territory), using the Analytical Hierarchy Process (AHP) as a multi-criteria decision tool for the evaluation of such KHIs. The methodology was validated by comparing its results with QRA results that involved Na-Tech events (Campedel et al., 2008). In this work, the sensitivity of the KHIs will be assessed, through the construction of specific case studies, in order to show the influence of certain variables upon the resulting values for scenarios related to fires, explosions and dispersion of toxic materials. In particular they will be analyzed:
the influence upon the KHIs of the seismic vulnerability of different kind of tanks (unanchored, anchored and pressurized) and for different values of Peak Ground Acceleration (PGA);
the influence upon the KHIs of the domino effect evaluated for different combinations of types of tanks (unanchored, anchored and pressurized);
the influence upon the KHIs of the volatility of different substances, classified as compressed/liquefied gases, high volatility liquid, low volatility liquid and dusts

1. Seismic vulnerability

The influence upon the KHIs of the seismic vulnerability of different kind of tanks (unanchored, anchored and pressurized) and for different values of seismic intensity (PGA) is analyzed through three simplified layout consisting of a single tank subjected to three different values of PGA. For these case studies the evaluation of KHIs will be addressed assuming that the mass of hazardous substances

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contained, expressed as a fraction of the limit defined in Article 8 of the European "Seveso II" Directive (The Council of the European Union, 1996), is equal to 1.

The types of tanks considered in the analysis are: atmospheric vertical cylindrical not anchored tanks (At-Un); atmospheric vertical cylindrical anchored tanks (At-An) and horizontal cylindrical pressurized tanks (PV).

The levels of horizontal ground acceleration (PGA) considered in the analysis, expressed as a fraction of the acceleration due to gravity g, are: 0.05 g;0.15 g and 0.25 g.

It is assumed that the atmospheric tanks contain a generic liquid substance classified by the method as flammable, highly volatile with high enthalpy of combustion, highly toxic and explosive, capable of generate scenarios such as pool fire, dispersion of toxic materials and VCE.The pressurized tank is assumed to contain a generic compressed / liquefiedgas classified as flammablewith high enthalpy of combustion, stored at low pressure, highly toxic and explosive, capable of generate scenarios such as gas fire, dispersion of toxic substance, BLEVE and VCE.

In Table 1 the results of the calculation of the Damage Probability for different tanks, calculated for different values of PGA, are shown. PGA is expressed as a fraction of gravity acceleration g.

Table 1: Values of damage probability DP_J for different tanks (rows) calculated at different values of PGA (columns).

	0.05g	0.15g	0.25g
At-Un	$2.29 \cdot 10^{-4}$	$2.11 \cdot 10^{-02}$	$8.89 \cdot 10^{-02}$
At-An	$3.65 \cdot 10^{-07}$	$5.54 \cdot 10^{-04}$	$6.66 \cdot 10^{-03}$
PV	$3.43 \cdot 10^{-07}$	$9.39 \cdot 10^{-05}$	$7.82 \cdot 10^{-04}$

The evaluation of the KHIs is based on the characteristics of hazardous substances contained into the storage tanks; using the qualitative methodology for the initial assessment of earthquake-related Na-Tech risk(Busini et al., 2011), the values of KHI_F, KHI_T and KHI_E, related to fires, explosions and dispersion of toxic substances, were calculated for the three situations considered; then, the values of the global Key Hazard Indicators (KHI_G) were calculated (Table 2) for the different types of tanks and plotted in Figure 1 to highlight the influence of the type of tanks upon the indicators varying the PGA.

Table 2: KHI_G calculated for different tanks (rows) at different values of the PGA (columns).

	0.05g	0.15g	0.25g
At-Un	$1.71 \cdot 10^{-03}$	$3.48 \cdot 10^{-02}$	$9.10 \cdot 10^{-02}$
At-An	$2.33 \cdot 10^{-05}$	$3.08 \cdot 10^{-03}$	$1.62 \cdot 10^{-02}$
PV	$3.66 \cdot 10^{-05}$	$1.54 \cdot 10^{-03}$	$6.34 \cdot 10^{-03}$

The comparison between KHIG obtained at different values of PGA shows that not anchored atmospheric storage tanks are the most vulnerable to the effects of an earthquake, from a seismic intensity of 0.05 g to 0.15 g the increase in the index is greater than one order of magnitude; increasing further the seismic intensity the KHIs become closer to their maximum value, 1, imposed by the asymptote for a failure for seismic reasons. The vulnerability of the anchored atmospheric storage tanks is lower than that of non-anchored; moreover, for low values of seismic intensity can be noted a very low vulnerability determined by the presence of the anchorage. The pressurized storage tanks, despite presenting lower probability of failure respect the other types of tanks, determine values of KHIs similar and generally slightly lower than those obtained considering atmospheric anchored storage tanks, this is due to the higher hazard assigned to the substances stored in pressure and classified as compressed / liquefied gas, which contributes to raising the value of the risk posed by the storage of these substances. It is so possible to observe how the KHIs respond correctly to changes in the vulnerability of tanks to the earthquake; this shows that, in case of earthquakes, having to do with substances to be stored at atmospheric pressure, it is better to opt for the anchorage of storage tanks.

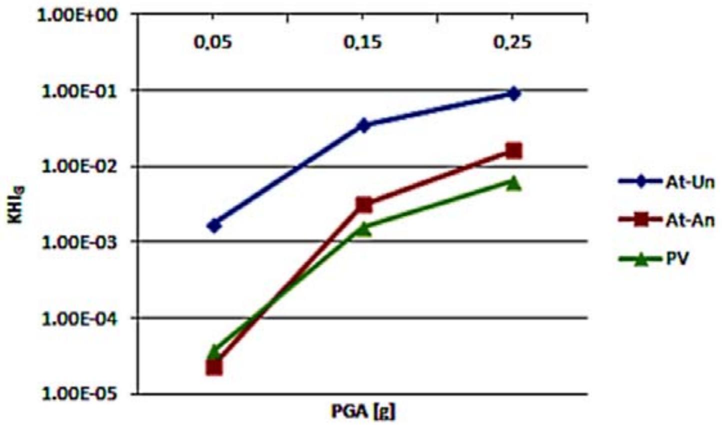

Figure 1: KHI_G calculated for the different types of tanks and at different values of PGA.

2. Vulnerability to the domino effect

The influence of the vulnerability of different types of tank to the domino effect upon the KHIs will be analyzed through 12 simplified layouts. It is assumed a PGA of 0.20 g for all layouts, which is a value big enough to trigger the collapse of the tanks so to potentially generate a domino effect, and a mass of dangerous substance contained in each tank, defined as the fraction of the limit defined in Article 8 of the European "Seveso II" Directive (The Council of the European Union, 1996), equal to 1. The types of tanks considered in the analysis are those mentioned in case 1).

For each type of tank, the KHIs will be assessed for: 1. only the considered storage tank; 2. the considered storage tank and a second pressurized storage tank; 3. the considered storage tank and a second atmospheric anchored storage tank; 4. the considered storage tank and a second atmospheric not anchored storage tank. Substantially 4 layouts will be shown for each type of tank in order to represent the effect of the presence of a second storage tank, in addition to the considered ones, on the values of the KHIs.

The substances contained into the tanks have the same hazard characteristics of those considered in case 1) and, consequently, can lead to the same incidental scenarios.

In Table 3 the values of the damage probability (DPJ) assumed by different tanks for a value of PGA equal to 0.2 g are showed. The conditioned probabilities (PJK), which describe the probability for an incidental scenario to propagate itself from the tank j to the tank k are posed equal to 1, which means that the domino effect will happen for sure. Using the damage probabilities in case of seismic event (DPJ) and the conditioned probability (PJK) in the equation for the calculation of the damage probability for the tank to collapse due both to seismic event and domino effect (DPK) (Busini et al., 2011), the total probability of collapse is calculated and reported in Table 3 at the side of DPJ.

The probability of failure show that the not-anchored atmospheric storage tanks are the most vulnerable to an earthquake, and, even if close to tanks with low seismic vulnerability, the value of the probability of total failure virtually does not change, whereas if the tank is close to another atmospheric not-anchored storage tanks the probability of failure almost doubles. The atmospheric anchored storage tanks show lower probability of failure respect to the not-anchored tanks and the proximity of low seismic vulnerability tanks (PV) practically does not affect its value while, if close to a not-anchored atmospheric tanks, an increase in the probability of failure of an order of magnitude is showed; this is due to the domino effect. The pressurized storage tanks are the less sensitive to seismic activity but if they are close to atmospheric storage tanks the total probability of failure increases significantly due to the possible spread of an accident from these tanks: if a pressurized tank is close to an atmospheric not- anchored tank, the probability of total failure of the first one increases of two orders of magnitude, becoming virtually identical to the probability of failure of the second one. The pressurized tanks, just for their strength, are the most disadvantaged in a potential domino effect caused by the collapse of more vulnerable tanks .

Table 3: Values of the total probability of collapse (DP_K) assumed by tanks subject to the domino effect caused by the presence of different types of tank at a PGA of 0.20 g. At-Un: atmospheric not anchored tanks; At-An: atmospheric anchored tanks; PV: pressurized tanks.

	Single tank (DP_J)	Total probability of collapse: second tankPV	Total probability of collapse: second tankAt-An	Total probability of collapse: second tankAt-Un
At-Un	$4.98 \cdot 10^{-02}$	$5.01 \cdot 10^{-02}$	$5.21 \cdot 10^{-02}$	$9.71 \cdot 10^{-02}$
At-An	$2.41 \cdot 10^{-03}$	$2.73 \cdot 10^{-03}$	$4.82 \cdot 10^{-03}$	$5.21 \cdot 10^{-02}$
PV	$3.22 \cdot 10^{-04}$	$6.43 \cdot 10^{-04}$	$2.73 \cdot 10^{-03}$	$5.01 \cdot 10^{-02}$

Table 4 summarizes the values of KHI_G calculated forthe considered layout, these values are plotted in Figure 2. The layouts are organized as follows: 3 consist of a single tank and 9 consist of a pair of tanks whose names appear in the rows and in the columns of the table. It is noted that some values are equal, this is due to the fact that of the 9 possible combinations of pairs, 3 of these are repeated.

Table 4: KHI_G values calculated for different layouts of pairs of tanks subject to the domino effect caused by the presence of different types of tank at a PGA of 0.20 g.

	Single tank	PV	At-An	At-Un
At-Un	$6.18 \cdot 10^{-02}$	$1.30 \cdot 10^{-01}$	$1.01 \cdot 10^{-01}$	$1.53 \cdot 10^{-01}$
At-An	$8.21 \cdot 10^{-03}$	$1.87 \cdot 10^{-02}$	$2.07 \cdot 10^{-02}$	$1.01 \cdot 10^{-01}$
PV	$3.51 \cdot 10^{-03}$	$8.84 \cdot 10^{-03}$	$1.87 \cdot 10^{-02}$	$1.30 \cdot 10^{-01}$

The atmospheric not-anchored storage tanks determine an high and quite stable value of KHI_G. In the first case the single atmospheric not-anchored storage tank determines by itself a KHI_G already high compared to other tanks. In case 2, the KHI_G is growing, not because of the spread of an accident from the pressurized tank to the atmospheric not-anchored ones but for the opposite reason, that is because the proximity of the atmospheric not-anchored storage tank makes the pressurized tank (containgitself a hazardous substance)very vulnerable. In cases 3 and 4, the presence of other atmospheric tanks contributes significantly to the determination of the KHIs.
Being less vulnerable, the atmospheric anchored storage tanks determine, by themselves, a KHI value of one order of magnitude lower with respect to the not-anchored. In case 2 the presence of a second pressurized tank results in an increased risk due, as mentioned, to its vulnerability to the domino effect. In case 3 the result changesa little, but in this case are the two atmospheric anchored tanks that determine the result. In case 4, the presence of a not-anchored storage tank causes an increase of the KHI of almost an order of magnitude.
Pressurized storage tanks are the least vulnerable to seismic events. In case 2 the presence of a second pressurized tank results in an increase in KHI_G mainly due to the hazards of the substance contained more than to the domino effect. In case 3 a further increase of KHI is due to the presence of an atmospheric tank, more vulnerable and thus able to increase the probability of total failure of the first tank, although the substance contained is less dangerous than a compressed / liquefied gas. In case 4 the presence of an atmospheric not-anchored storage tank, highly vulnerable to an earthquake, trigger an increase in $KHI_G$of another order of magnitude.

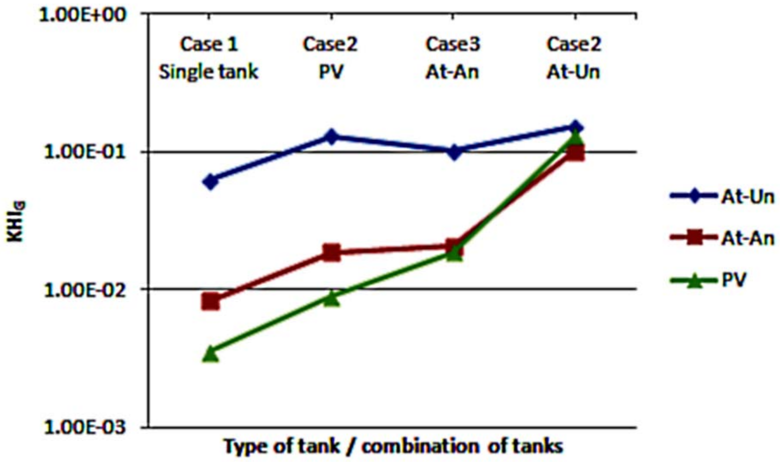

Figure 2: KHI_G values calculated for different layouts of pairs of tanks subject to the domino effect caused by the presence of different types of tank at a PGA of 0.20 g.

The analysis show that the model responds plausibly also to the possibility of a domino effect.It is therefore possible to deduce that the presence of tanks highly vulnerable to the effects of an earthquake is predominant in case the safety distances are not respected in the design phase.Is therefore always advisable to comply with these distances.

3. Volatility of the substances

The influence of the volatility ofthe substances on KHIs is analyzed by means of simplified layouts consisting in a single tank.KHIs for substances with different volatilities and classified as: compressed / liquefied gas, high volatility liquids, low volatility liquids, solids / fine dusts will be evaluated.

Substances classified as compressed / liquefied gas are contained in pressurized tanks, all other substances are assumed to be contained in atmospheric not anchored storage tanks. For what concern the substance contained into the pressurized tanks, it has the same hazard characteristics of that considered in case 1) and, consequently, it can generate the same incidental scenarios. Also for the atmospheric storage tanks the substance will be the same except for the volatility that will be varied; the incidental scenarios will be so related to the volatility class, in particular low volatility liquids can lead to pool fires and dispersion of toxic substances while solids / fine powders can lead to fires of solid material, dispersion of toxic substances and VCE.

In the evaluation of KHIs will be assumed a mass of dangerous substances, expressed as a fraction of the limit defined in Article 8 of the European "Seveso II" Directive (The Council of the European Union, 1996), equal to 1 and failure probabilities will be calculated for a PGA of 0.20 g.

The values of the Damage Probability (DP_J) for atmospheric unanchored storage tanks (At-Un) and pressurized tanks (PV) are shown into the first column of Table 3 (Single tank). The KHis that can be obtained for substances with different characteristics of volatility and for a PGA equal to 0.2 g are shown in Table 5 and plotted inFigure 3.

In this situation it can be seen that, due to the low vulnerability of pressurized tanks, despite the higher danger posed by the physical state of the substances contained, the KHIs related to compressed / liquefied gas are lower, by at least one order of magnitude,than the other cases. High volatility liquids have all the KHIs of two orders of magnitude higher than the compressed / liquefied gas because of the different seismic vulnerability of non-anchored storage tanks. Low volatility liquids show similar values of KHI_I and KHI_T, because of the similarity of the two hierarchies, while the KHI_E is zero(it has been considered that low volatility liquids cannot lead to explosives phenomena). Substances classified as solids / fine dusts show KHIs similar to those shown by low volatility liquids; to note is that the KHI_T is, even if only slightly, higher than that estimated for fires, this to indicate the greater danger of the first scenario.

Table 5: KHIs calculated for substances with different characteristic of volatility and for a PGA equal to 0.2 g.

	Case 1: Compressed / liquefied gas	Case 2: Highly volatility liquids	Case 3: Low volatility liquids	Case4: Solids / fine dusts
KHI_F	$1.21 \cdot 10^{-04}$	$1.16 \cdot 10^{-02}$	$5.41 \cdot 10^{-03}$	$1.60 \cdot 10^{-03}$
KHI_T	$1.43 \cdot 10^{-04}$	$1.00 \cdot 10^{-02}$	$3.85 \cdot 10^{-03}$	$3.86 \cdot 10^{-03}$
KHI_E	$8.93 \cdot 10^{-05}$	$1.22 \cdot 10^{-03}$	$0.00 \cdot 10^{+00}$	$4.96 \cdot 10^{-04}$
KHI_G	$3.51 \cdot 10^{-03}$	$6.18 \cdot 10^{-02}$	$3.53 \cdot 10^{-02}$	$2.60 \cdot 10^{-02}$

Although the volatility of a substance cannot be chosen but depends on the type of substance and on the storage conditions, we can see how the method responds effectively to the decreasing of the volatility (and therefore of the risks posed by the substance) with the decreasing of KHIs. Compressed and liquefied gases, although pose greater risks due to their extreme volatility are, by necessity, stored in pressurized tanks, which, however, are more resistant to the effects of an earthquake; the result is that their higher risk is abundantly compensated.

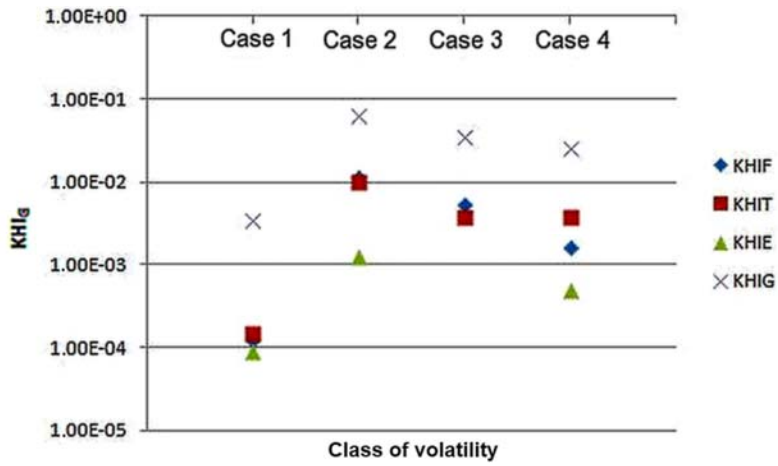

Figure 3: KHis calculated for substances with different characteristic of volatility and for a PGA equal to 0.2 g.

4. Conclusions

In conclusion, the model shows appreciable changes to the variation of the considered parameters, thus it is able to represent a large series of cases.

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