Post-Emergency, Multi-Hazard Health Risk Assessment in Chemical Disasters
PEC

Deliverable D. E. 2

Guidelines for risk mitigation of buildings and plants

ECHO/SUB/2015-713844-PREV11 - PEC: Post-Emergency, multi-hazard health risk assessment in Chemical disasters
Project co-funded by ECHO - Humanitarian Aid and Civil Protection

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1 INTRODUCTION

The present report has the purpose of providing some practical guidelines to reduce the risk in Petrochemical Plants and is based on the outcomes of the previous tasks developed in the PEC project with particular reference to:
- Task B.1 "Definition of the structural models and seismic fragility analysis techniques available for the specific case study",
- Task B.2 "Report on the Evaluation of Possible Damages Suffered by Chemical and Process Vessels due to Floods"
- Task B.4 "Evaluation of possible damages suffered by critical structures and infrastructures as consequence of a terroristic attack".

The present report mainly deals with tanks, horizontal and vertical vessels and piping systems.

The Risk is usually defined as the product of: hazard, exposure and vulnerability and it is treated separately in the PEC project depending on the hazard: seismic, flood or man-made.

Seismicity indicates the frequency and force of earthquakes and represents a physical characteristic of an area. If we know the frequency and the energy of the earthquakes that characterize a certain area and we attribute a value to the probability of a seismic event of a given magnitude occurring in a certain interval of time, we can calculate the seismic hazard. The greater the seismic hazard, the more probability there is of an earthquake occurring of great magnitude in the same interval of time.

The consequences of an earthquake also depend on the resistance of buildings to the effects of a seismic tremor. A building's potential for damage is called vulnerability. The more vulnerable a building is (due to its type, inadequate design, poor quality materials and construction methods, lack of maintenance), the greater the consequences will be.

Finally, the number of assets exposed to risk, the possibility in other words of damage in economic terms, to cultural heritage or the loss of human lives, is called exposure.

As it is clear from the definitions of hazard, exposure and vulnerability, in the seismic risk of petrochemical plants, the vast majority of the attentions is related to the vulnerability: indeed the hazard is an intrinsic property of a site and the exposure is often governed by functionality reasons.

A **flood risk** analysis involves the assessment of the probabilities of flooding, as well as the consequences of flooding (Van Gelder, 2013). Floods can be caused by a number of different mechanisms, such as extreme precipitation with high intensity and prolonged duration, snowmelt, coastal floodings by extreme storms and wind set-up or tsunami, and dam breaches. For a proper hazards or risk analysis, the probabilities of these events should be estimated.

Typically, the assessment of the probability is done by observational data analysis, while consequences assessment is made with physical-based modelling. When stream-gauging records are insufficient or absent, flood hazard assessments based on direct measurements may not be possible, because there is no basis to determine the specific flood levels and recurrence intervals for given events. Hazard assessments based on remote sensing data, damage reports, and field observations can substitute when quantitative data are scarce.

As far as **man-made risk** is concerned, when assessing loss of containment events from a process plant, scenarios of leakage derived by causes related to human action have to be taken into account. Human action plays a crucial role in this evaluation since usually most likely causes of loss of containment are the ones related to human action. The causes of loss of containment related to human action/presence can be divided in four main categories: errors in design, construction, maintenance; not voluntary errors by plant operators; sabotage; terrorism.

2 EXPOSURE

With regard to the Exposure, a beneficial effect to the risk reduction can be obtained by adopting the following precautions:

- Limit the domino effect in the design positioning the tanks and vessels not too close one to other. In this case, the failure of one of this item remains confined in a limited area;
- Limit, in conjunction also with functionality considerations, the volume of hazardous material which can be loss in event of a leakage (i.e. by limitation of the dimension of the elements containing hazardous materials;
- Limit the number of elements connected in series and increase the redundancy of the connections between the different elements in order to reduce the potential domino effect.

3 HAZARD

3.1 Seismic Hazard

The **seismic hazard** is a property of a site and as such is difficult to operate on it in order to reduce the seismic risk connected to a petrochemical plant. In general, the Engineer can operate in order to better define the seismic hazard and avoid the sites with high seismic risk or with liquefaction potentials. In general, the following are the main points of considerations:

- Hazard analysis should cover definition of ground shaking, excessive ground deformations or ground failure caused by fault rupture, liquefaction and landslides, tsunamis;
- A correct definition of the soil dynamic properties based on accurate in situ tests, as well as the definition of the topographic effects;
- For particular case, even in cases with high seismicity or with large amount of dangerous materials, a site-specific seismic design spectrum should be defined rather than use a standard code-based approach. A site specific seismic design spectrum can be defined either with Probabilistic Seismic Hazard Analysis (PSHA) or with Deterministic Seismic Hazard Analysis (DSHA);
- Avoid locating the petrochemical plant in areas locate in proximity to faults, in cliff areas and based on soils subjected to liquefaction.
- The identification of the area for a petrochemical plant shall take into consideration the presence of steep slopes with potential stability problems. If possible, these areas should not

be selected for the location of the plant, otherwise detailed slope-stability studies are recommended.

- The correct identification of the effect of the soil condition on the Design Response Spectrum. To this aim a site response analysis can be developed with one on the following three methods. The first approach is the direct use of an attenuation equation that is representative of the subsurface conditions in the PSHA or DSHA process. The second approach for modelling local site effects is first computing rock outcrop (surface rock) response spectra using a rock attenuation equation and then modifying the rock spectrum by generic soil amplification factors such as the F_a and F_v factors in ASCE 7 or the S_s factor of Eurocode 8 (EC8-1, 2006). The third approach for modelling local site effects is through a detailed dynamic site response analysis. Such an analysis is performed when soil condition cannot be reasonably categorized into one of the standard site conditions or empirical site factors for the site are not available. Dynamic site response analysis can either be one-dimensional analysis that assumes vertically propagating shear waves through the various subsurface soil layers or two-dimensional analysis.

3.2 Flood Hazard

The **flood hazard** needs to be defined depending of the property of the site with respect to the main causes of floods: dam breaks floods, coastal storm surges and river floods. Each of these phenomena needs to be quantified with respect to defined average return periods. In the case of river floods, the hazard is defined in terms of the Intensity-Duration-Frequency curves that provide information on the likelihood of heavy rainfall events of various amounts and durations. For dam breaks, different scenarios need to be defined and, based on the topography of the area, the water depth in the petrochemical plant can be defined.

Determining flood hazard is a combination of the following steps:

1. Determine the flood characteristics for a given event, which can be extent only, or a combination of extent and depth, or even a combination of extent, depth and flow velocity. The available information on the characteristics of a flood depends on the method used. The information needed depends on the hazard interpretation (evacuation, building damage, early warning etc.);
2. Determine the probability of occurrence of each flood, so that the flood characteristics can be linked to a recurrence interval. Some methods are not able to do this, in which case the analysis becomes a flood susceptibility analysis, rather than a hazard analysis;
3. Translate flood characteristics into a hazard. The hazard level is an interpretation of flood information, and depends on the type of hazard information needed, the degree of exposure and the type of elements at risk.

In order to increase the accuracy of the hazard identifications and to reduce the risk related to flooding, the following are the main aspects to be considered:

- Hazard analysis should cover all the potential natural events such as river flooding, dam breaks, coastal storm surges depending on the location of the plants. Domino effect shall be included in the analysis;

- The hazard analysis shall cover all the aspects that may affect the flooding risk: meteorological forecasting, hydrological model and hydraulic model;
- The hydrological model can be defined with different levels of complexity depending on the accuracy required and on the expected results. The simplest model can be the use of Instantaneous Hydrograph Model (IUH). A more complex model could be the use of a conceptual model such as that developed by Zhao, (1994). Finally, the most refined model is the Physically based model. Different applications of the physically based model are: TOPKAPI (Topographic Kinematic Approximation and Integration) model is a fully-distributed physically-based hydrologic model that can provide high resolution information on the hydrological state of a catchment, such as flow and soil moisture; TUFLOW software employed for floodplain delineation based on an implicit 2D solver (Stelling 1984, Syme 1991). It solves the full two-dimensional, depth averaged, momentum and continuity equations for free-surface flow using a 2^{nd} order semi-implicit matrix solver.

3.3 Man-Made Hazard

As far as man-made hazard is concerned, the causes of loss of containment related to human action/presence can be divided in four main categories:

- errors in design, construction, maintenance;
- not voluntary errors by plant operators;
- sabotage;
- terrorism.

All of these items need to be identified and quantified in a systematic way. Different methods for the quantifications of the man-made hazards are available such as: Hazard Identification Study (HAZID) or the Hazard and Operability Analysis (HAZOP).

The possible consequences of hazardous situations that may occur on a petrochemical plant can be summarized in air and water pollution, fire scenarios or explosion, and injury to personnel. In a petrochemical plant, there are several interrelationships of events, conditions and sources that can lead to these three consequences. The goal of a safe facility design is to reduce the risk of each of the identified hazards to a reasonable level generally defined ALARP (As Low As Reasonably Practicable) (API 14J, 2007).

Since the Risk is the product of probability of occurrence and consequences, Risk Reduction is done by reducing the probability of occurrence of those events and/or minimizing their consequences. In this framework, the main principles for safe petrochemical plants design and operation are:

- minimizing the likelihood of uncontrollable releases of hydrocarbons and other hazardous materials;
- minimizing the chances of ignition;
- preventing fire escalation and equipment damage;
- providing for personnel protection, escape and rescue.

Hazard connected to design, construction and maintenance can be reduced by developing dedicated Hazard Analysis on the plant. Hazards analysis is a systematic procedure for identifying, evaluating and controlling potential hazards in a petrochemical plant. A hazards analysis program should be applied to all phases of the life of a facility from project inception through abandonment to assess potential hazards during design, construction and operation in order to minimize the risk of personnel injuries, loss of equipment, and damage to the environment.

It is important to identify hazards as early as possible; time is needed for adequate study and evaluation before determining the most appropriate solutions to approach the identified hazards. It is relatively easy and inexpensive to make modifications early in the design stage of a project, when changes can be incorporated with minimal effect on cost or schedule.

The normal and easiest method for hazards analysis in an early design phase by compliance with standard practice is using checklists. The checklist help determine that design standards and practices are met and that previously recognized hazards are properly addressed. It is quick and easy to use and it results effective for control of common hazards. It can also be used during any stage of a project life cycle (design, construction, startup, operation, and shutdown). The checklist is usually prepared by experienced personnel familiar with the design and operation of the petrochemical plant and following company and industry standards and procedures. Checklists shall be audited and updated regularly to incorporate new experience by the company and industry, including the results of accident and incident investigations.

In addition to checklists, different hazard analysis method have been developed by recommended practices (API 14J, 2007) and are suggested to be applied in the further phases of the design and during the life of the plant.

Low risk facilities such as single well caissons and most unmanned wellhead platforms with minimal process equipment can be analyzed using a simplified checklist. Higher risk facilities, including all manned facilities, can be analyzed using more detailed checklists.

When the checklist analysis identifies areas that cannot be resolved and require further evaluation, other methods such as What-If, HAZID, HAZOP, or Fault Tree Analysis can be used. These methods should be utilized to analyse specific areas or events and not as a complete analysis in themselves. They should generally be limited to analysing the following areas: new processes, complex control systems, toxic material processes, unusually high risk to personnel or environment.

When a facility contains new equipment or processes without previous experience, a HAZOP and FMEA should be considered to identify hazards associated with these areas.

If a specific undesirable event is to be studied more closely, a Fault Tree Analysis or other methods should be considered.

The outcomes of the Hazard Analysis allow calculating the risk by crossing the results with the consequences. A typical risk matrix is reported in figure below.

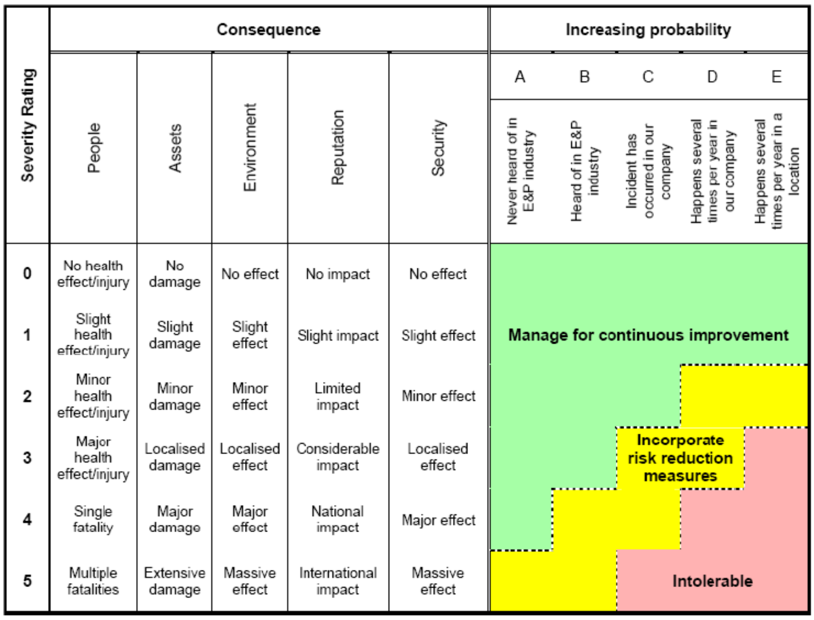

Figure 3-1: Typical Risk Matrix for a Petrochemical Plant

Hazard connected involuntary errors by plant operators can be reduced by adopting the following main actions.

- Developing a strong operational safety culture (training and information of personnel) in facilities, which is at the heart of business operations, and understanding the risks posed by organizational activities dealing with hazardous substances.
- Enhance the level of preparedness of the employees and of the managers with respect to all the safety measures to be applied during design phases and normal operations. Indeed, the design and equipment layout of petrochemical plants are usually complex. Design personnel should be knowledgeable of special safety considerations concerning simultaneous operations, toxic gas and gas processing when these are part of the production operations.

4 SEISMIC VULNERABILITY

The present paragraph report considerations related to seismic vulnerability of petrochemical tanks, horizontal pressure vessels, vertical pressure vessels and piping. For each of these items, specific suggestions are reported for the design, construction phase and retrofit intervention on existing facilities with the purpose of reducing their seismic vulnerability.

4.1 Tanks Vulnerability

The present paragraph has the purpose of providing indications to reduce the seismic vulnerability of petrochemical tanks.

Field observations in the aftermath of recent and past earthquakes have shown the seismic vulnerability of storage steel tanks. These observations highlight structural deficiencies that are mostly related to the lack of structural seismic design and detailing, lack of redundancy, and inadequate anchorage design and execution (see e.g. Swan et al., 1984; Manos, 1991; Zareian et al., 2012; González et al., 2013; Brunesi et al., 2015). If damage/failure mechanisms of existing tanks reveal how vulnerable these items are to earthquake-induced actions, the set of fragility models derived in a previous deliverable (i.e. PEC - Deliverable D.B.1) has corroborated this consideration even further, thus implying the need for risk mitigation guidelines applicable to both existing tanks as well as tanks of new construction.

In this respect, measures/actions can be suggested, anticipating that the proposals described and discussed in what follows make use of the outcomes of (i) incremental nonlinear dynamic analyses of both mechanics-based finite element models and high-definition finite element models, the latter ones being able to reproduce/predict stress/strain concentrations and hence damage of critical portions of the structure; (ii) fragility functions that provide the probability of reaching or exceeding multiple damage state conditions for a given seismic intensity, with the latter functions being derived by considering a large portfolio of randomly generated items so that uncertainties in system capacity can be modelled and propagated; (iii) quantitative risk analyses that result in the evaluation of seismic risk associated with damage conditions of interest, namely the probability of reaching those conditions in a timeframe of one year and/or the mean annual frequency of occurrence of each single damage condition.

Different types of damages and failure have been observed during the past earthquakes for steel tanks containing petrochemical products. It has to be noted that in general these tanks, especially unanchored tanks, are particularly susceptible to many kinds of damages during earthquakes. This is mainly because a great part of the mass contributes to the overturning moment, but only a small portion of the mass contributes to the overturning resistance.

The most frequent tank failures due to earthquake are hereafter presented. In the following paragraphs, recommendations to prevent these failures and reduce seismic vulnerability are reported for design and construction phases and for retrofit interventions on existing tanks.

- A common failure mode in tanks has been breakage of piping connected to a tank as a result of relative movement between the tank and the nearest pipe support. Alternatively, if the piping is stronger than the tank wall or baseplate to which it is connected, tearing of the wall or baseplate may result.
- Partial loss of contents may result where a vertical pipe is rigidly connected to the ground or foundation and supported rigidly along the wall of the tank.

4.1.1 Design and Construction phase

The first requirement for the design of new tanks is following the indications of international standards for seismic design of tanks. Tanks of new construction can be designed in accordance with internationally recognized modern seismic design Codes and Standards (e.g. EC8-4, 2006; NZSEE, 2009; AWWA D103, 2009; AWWA D100, 2011; API 620, 2012; API 650, 2012; AIJ, 2010) and can be analysed through the most rigorous computational methods, whilst existing storage tanks require more attention and the use of specific technological solutions. Nowadays, the design process can be carried out using a Standard adequate to the characteristics of the tank of interest (i.e. type, shape, material and support/base connection), in compliance with the most sophisticated and largely upgraded capabilities of finite element analysis, potentially accounting for fluid-structure interaction and soil-structure interaction. Thus, it can be inferred that tanks of new construction are potentially safe, if properly designed and detailed. In this respect, particular care should be paid earthquake resistant design of both (i) the tank wall and (ii) the base connection. As far as the former is concerned, use can be made of European rules to prevent elastic and elastic-plastic mechanisms from occurring for a given seismic demand, with the latter being computed in terms of hydrodynamic pressure distribution along the height of the tank according to the European provisions (EC8-4, 2006). For what concerns the design and detailing of the base connection, simple equilibrium equations can be used to predict the overturning moment and the base shear corresponding to the activation of sliding of the tank with respect to the ground/foundation. Bolts and plates can be designed and sized using codified criteria available in European prescriptions for bolted connections (e.g. EC3-1-8, 2005).

More practically, specifically during the design phases, the following details and precautions shall be adopted in order to reduce seismic vulnerability of tanks. Some of these indications are devoted to the design phase, while others are referred to both design and construction phases being mainly connected to technological aspects.

- Inclusion of Soil Structure interaction in the design phase. Tanks, if designed with a fixed base approach, have period of vibrations that are in the first branch of the response spectrum prior to the plateau. The inclusion of Soil Structure interaction effects can lead to a period lengthening with the result of an increment of the seismic acceleration because the period of vibration of the tank-foundation-soil system can be now located in the plateau (zone with constant acceleration).
- Increase in the freeboard height, which implies a decrease in the volume of fluid stored in a tank and the subsequent reduction of seismic actions upon the tank under consideration. Clearly, such an intervention minimises the costs associated with business interruption, but it does not provide the tank with any sort of additional capacity/redundancy because the intervention itself is simply based on a reduction of the seismic demand. By contrast, it is evident that both impulsive and convective components of motions can be simultaneously reduced because of the reduced height of the fluid or, more in general, of the material stored in the tank.
- Installation of seismic isolators at the base of the tank. In this case, the structure is protected from earthquakes by isolation systems that are able to disconnect the ground and the structure in terms of horizontal displacement/acceleration while maintaining sufficient stiffness in the vertical direction. This strategy requires the consideration of enough space under the tank for inspections and the application of restrainer for the repositioning of the tank after a seismic event. The use of seismic isolators has to consider the horizontal displacement of the tank with particular reference to the connected piping;
- Use of fluid viscous dampers installed at the top of the tank wall and acting against its floating roof so that the sloshing motion of the stored fluid can be controlled. The design of an intervention of this type should take into account that stress concentrations may take place in

both the tank wall and the connection between wall and dampers. As far as the hydrodynamic behaviour of the tank-fluid system is concerned, it can be inferred that this response mitigation strategy is more effective in limiting the effects associated with the convective component of motions. Hence, the height of the sloshing wave can be reduced;

- Installation of flexible pipe-tank and pipe-pipe joints. Given their nature, pipelines are usually more susceptible to differential movements in their supports than to induced inertial forces. Accordingly, flexible connection systems can be provided between both the pipe segments as well as the pipeline and the tank, in such way that the response of different structural items is decoupled and their relative displacements are accommodated;
- Design the tank system in order to avoid uplift of the tank base. Indeed, if uplift occurs, an anchoring system is required and this has to be properly designed to resist seismic force. In addition, the presence of tension forces under the tank base causes additional vertical stresses in the tank walls;
- Careful consideration of the anchoring details in case of tension forces at the base: reduction of the eccentricity between anchor bolt and tank wall, use of welding subject to shear and not to tension, reduction of the additional out of plane stresses to the tank walls.

4.1.2 Retrofit of Existing Structures

Reducing the vulnerability of the existing tanks is of primary importance in reducing their seismic risk. In this context, it is worth mentioning that existing tanks similar to those severely damaged during the 2012 Emilia seismic sequence (and other ones) still represent the most common form of storage structure in the Italian context (and in other European and non-European countries), which implies that specific considerations should be made on risk mitigation actions (i.e. active and passive measures/devices) applicable to structural systems of this type. Firstly, it should be pointed that all the criteria previously proposed for tanks of new construction can be used, in this case, for the assessment of existing tanks, namely to evaluate and quantify their structural deficiencies in comparison with the counterpart newly designed systems. This constitutes the background information for any structural upgrading intervention and also permits one to identify the most suitable type or method of strengthening/upgrading.

The foremost strategies, including active and passive approaches, can be adopted to reduce seismic vulnerability:

- Strengthening of the base connection. This is an upgrading method that can be implemented for the case of poorly anchored tanks (or even unanchored ones) and it simply consists of dismantling the poorly designed/detailed connections at the base of the tank and replacing them with properly conceived bolted joint systems. Their resistance can be computed according to conventional component-based methods available for these connections and should account for any additional seismic demand that can be transferred between the tank wall and the connection. The load transfer mechanisms between the connection and the foundation should be considered as well.
- Strengthening of the tank wall. This type of structural upgrading can be obtained by erecting an additional/external wall and by ensuring the stress/force transfer between the inner wall and the outer wall through the injection of grout/concrete in-between the two walls. It is

worthwhile to mention that this type of retrofit strategy can be easily implemented and also that the desired additional resistance can be obtained by properly selecting the resistance of the material used for the injection grout and the distance between the inner and outer walls, namely the total thickness of the resulting composite section.

- Substitution of the pipe to tank connections with flexible connections;
- Installation of seismic isolators at the base of the tank. This strategy implies that the tank should be uplifted so as to permit the installation of a number of isolation devices in correspondence to key positions underneath the base plate. As such, the base connections should be dismantled and the base plate of the tank should be strong enough to permit uplifting.

In closing, the abovementioned structural upgrading interventions can be referred to as the easiest and most conventional actions that can be implemented for mitigating the seismic vulnerability of storage steel tanks such as those pertaining to the two industrial plants under consideration. Needless to say that they can be implemented separately or, alternatively, the desired intervention can be the result of a combination of multiple actions.

4.2 Vessels Vulnerability

The present paragraph has the purpose of providing indications to reduce the seismic vulnerability of vertical and horizontal pressure vessels.

Concerning vessels, damages due to earthquake events were mainly observed in connection between piping and vessels, and in foundation anchoring. Effects of seismic events, even if of moderate intensity, were increased by the fact that the vast majority of the industrial plant equipment were designed for gravity and function loads only.

In Paolacci, (2013) an overview of the response of different items in petrochemical plants is also described. The most frequent damages in case of seismic event are the anchor bolts failure at the foundation due to the excessive actions, and the loss of contained fluids because of the failure of connected flanges due to excessive relative displacements. Failure due to local buckling at the skirt level was also observed.

From the previous references the following conclusions are possible. Although the performance of a specific plant, structure or component, is case dependent since the number of factors influencing the response is considerable, the repetition of some failure modes makes possible the following summary.

The failure of vessels is rarer than failure of piping. Failure modes have been attributed to:

- Unanchored equipment;
- Yielding of anchor bolts;
- Failure in shear of anchor bolts with consequent move up of vessel;
- Failure in the connection between piping and vessels

- Buckling at the skirt level.

4.2.1 Design and Construction

The first requirement for the design of new pressure vessels is following the indications of international standards for seismic design of these items. The majority of the standards regarding pressure vessels mainly addressed the design from the static and functional point of view only. For the time being, there are not specific standards that deal with seismic design of pressure vessels. Indeed, as far as seismic analysis of pressure vessels is concerned, in Europe the main code that provide general rules for the estimation of the seismic actions in industrial equipment is the Eurocode 8 part 4. Eurocode 8 part 4 Annex A provides a methodology for calculating hydrodynamic forces due to a seismic event.

As previously reported in PEC - Deliverable D.B.1, the provision for vertical containers can be employed for the vertical pressure vessels. However, when the height to diameter aspect ratio is large, sloshing effects can be neglected, considering also the presence of equipment inside the vessel. In United States, ASCE/SEI 7-10 (ASCE, 2010) includes pressure vessels in Chapter 15 for non-building structures. In that Chapter, guidance is given for design requirements of pressure vessels and the selection of seismic factors for calculating the base shear. Various types of vessels are addressed, such as elevated vessels on leg or skirt supports, horizontal saddle-supported welded steel vessels and vessels supported on structural towers similar to buildings and the behaviour factors are given. Some of the rules reported in ASCE 7-10 are also explained in FEMA P750, (2011) and FEMA P751, (2011). In these two documents, detailed rules are given for the estimation of the fundamental period of vibration of vertical pressure vessels and for the definition of the seismic base shear and overturning moment. In Italy, the Italian Society for the Industrial constructions provides indication for the seismic vulnerability analysis of industrial equipment with reference to the requirements reported in the Direttiva 2012/18/UE "Seveso III".

Specific indications to be adopted in the seismic design of pressure vessels are reported in the following paragraphs, considering both horizontal and vertical pressure vessels.

For both horizontal and vertical vessels, the connections between the vessel and the piping shall be flexible enough to accommodate differential movement of vessel and piping during the seismic event preventing the punching.

Horizontal Vessels

- Detailed consideration of the base connections. Horizontal vessels and exchangers are normally supported on two pedestals supporting saddles conforming to the vessel curvature. One saddle is fixed to the pedestal and the other is allowed to slide for thermal expansion. In previous failures of horizontal vessels, the transverse direction has resulted in most of the cases the weakest. A adequate ductility and redundancy of the base connections is then recommended;
- Capacity Design Considerations. Historically, the foundation anchor bolts for vessels and stacks have tended to stretch beyond yield when subjected to strong ground motion. Yielding of anchor bolts probably prevented collapse of these vessels.

Based on this experience, it is recommended that these anchor bolts should be designed with ductile embedment into the foundation. Special care should be taken to not oversize the anchor bolts. Excessively oversized anchor bolts could remain elastic during a seismic event, creating overturning moments in the foundation beyond that used in the design. This also leads to other detrimental behaviour such as buckling of the skirt. The weakest element of the chain constituted by anchor bolt, skirts, vessels, foundation should be carefully identified as the one with the biggest ductility capacity. The yielding of the anchor bolts is usually the expected mechanism for this regard and the one for which energy dissipation is considered. All the other elements shall remain elastic under the seismic event and shall be designed considering the strength of the ductile element including potential over-strength of the material;

- Inclusion of Soil-Structure Interaction. Since horizontal vessels are mainly founded on shallow foundations and due to the high stiffness of the vessel /supporting system, a soil-foundation structure interaction analysis is recommended;
- Consideration of local bending and buckling of the saddle supports. Horizontal pressure vessel on saddle supports designed for high internal pressure have an inherent thick shell to withstand internal pressure and could therefore endure high seismic loads (INDUSE, 2013). Nonetheless, their typical mode of failure is buckling at the saddle support or the shell near the saddle. Local bending and buckling of the saddle supports due to seismic load could also occur and shall be taken into consideration in the design.
- Consideration of reinforcing rings. Reinforcing rings are recommended for large pressure vessels and for pressure vessels located in high seismicity areas. These reinforcing rings as well as increased thickness of the vessel increases the capacity of the vessel to endure seismic loading. Caution shall be taken when deciding the area of the saddle reinforcement as the adjacent shell area is expected to fail in the case of no internal pressure. For this analysis, a simplified model of a single support and part of the vessel could be analysed instead of the full structure.

Vertical Vessels

Vertical pressure vessels are typically mounted on steel skirts and anchored to concrete foundations. Specific suggestions to limit the vulnerability of vertical vessels are reported below.

- Design considerations for the connections. Strength and ductility shall be provided to the anchorage in order to avoid fragile failure of the vessel connection;
- Design considerations for the skirts. The design of the skirts of vertical pressure vessels shall be carried out in order to assure a skirt strength higher than the one of the base connection. Indications for skirt design and buckling safety are reported in Eurocode 3 – Part 1-6 and Eurocode 8 Part 4;
- Capacity design considerations: considerations developed for the horizontal vessels are applicable also to vertical vessels;
- Definition of the Dynamic Behaviour. The calculation of the fundamental period of the vertical vessel is extremely important in the seismic design of these items. From previous studies, it has been assessed (PEC - Deliverable D.B.1) that base connections modelling have a significant impact in period calculation. Indeed, fixed base constraint can be not appropriate

for modelling vessel supports and multi-linear plastic link provide values that are more realistic.

4.2.2 Retrofit of Existing Structures

It is possible to reduce the seismic vulnerability also on existing vessels. Here below some general considerations are reported.

- Replace the rigid pipe/vessels connections with flexible connections;
- Strengthening of the vessel wall base and skirt especially for vertical vessels;
- Strengthening of the base connections and increment of their energy dissipation capacity;
- Base isolation: especially for horizontal heavy vessels, the seismic isolation at the base can increase the period of vibration of the element leading to a reduction of the seismic acceleration on the connection and on the vessel foundation;
- Passive control techniques: the application of passive control techniques to seismic retrofit of horizontal and vertical vessels is discussed in Paolacci et al, (2013) in which tuned mass dampers and damping inserted in bracings are presented. In addition, the possibility to include dissipation energy devices in the links between different elements appear also interesting.

4.3 Piping Vulnerability

Piping systems considered in the present report are mainly referred to: piping elements connected to tanks and vessels and pipe racks.
Piping systems represent a vital part of energy industries, e.g. petrochemical, oil & gas and chemical plants, where they are often employed to transport dangerous goods like oil and gas. A single failure in such systems may cause serious accidents both to the environment and human lives. During past earthquakes, piping systems and their components suffered significant damages causing severe consequences, as reported in several publications.
Damages observed in past earthquakes are mainly related to different aspects: failure of the connections between elements, failure of bolted flange connections, failure of the connections between pipe and tanks or vessels, failure of the piping supports or of the pipe racks.

4.3.1 Design and Construction

Several design codes exist for piping systems and are reported in the Table 1:

Table 1 Existing codes for the Design of Piping systems

American Codes	European Codes
ASME B31.3 (2006)	EN 1998-4 (2006)
ASME B31.1 (2001):	EN 13480-3 (2002)

- ASME SecIII Div1 (2002) - FEMA 450 (2003)	

Some considerations are required from the overview of the existing codes:

- Current design Standards have been found over-conservative for seismic applications and modifications have been proposed (Touboul et al., 2006);
- Some components, e.g., Bolted Flange Joints, do not have seismic design rules;
- Seismic input selection method is not clearly indicated in present codes.

Based on the analysis of the existing codes and on the available literature, the following aspects are the main properties that might be considered in the seismic design and construction of piping elements.

- <u>Accurate consideration of the piping mass in the design phase</u>. If software, using a beam-spring model, is used, the model normally converts each element associated with the piping from a continuous beam element between nodes to stiffness between two masses. Supports and anchors are modelled by adding additional stiffness to the mass node. The masses assigned are only half the sum of all element masses framing into the node. The accuracy of the model can be increased by the addition of just a few mass points to the system;
- <u>Accurate definition of the elbows and fittings in the design phase</u>. The straight branches of pipes are usually modeled as elastic beam finite elements with hollow circular section for which the beam theory is usually accepted. The elbows can also be modeled as beam element but modifying the stiffness and stress using the Flexibility Factor and the Stress Intensification factor. Alternatively, thin-shell elements can be used for the elbows using rigid links to attach the elbow to the straight parts of the pipe. The accuracy of the modelling approach can finally be increased by using "pipe" element available in different commercial structural analysis software;
- <u>Coupling effect between supported (piping) and supporting elements (pipe rack).</u> As far as seismic design of pipe racks system is concerned, it is noted that usually the piping analyses is separated from the steel fram of the pipe rack. In this case, the error is double. On one hand, the seismic actions on the pipe elements are not correctly estimated because the flexibility of the supports are neglected and the dynamic interaction of the pipe rack is not considered. On the other hand, the seismic actions on the pipe rack considers only the pipes as additional masses neglecting their stiffness. Depending on the frequency and mass ratios between supported/supporting elements, the coupling effect between piping system and main structure can be important or negligible. Detailed analysis of the dynamic coupling between piping systems and pipe rack can be found in INDUSE, (2013) and in Cademartori et al, (2017).
- <u>Accurate consideration of the stiffness of the boundary conditions.</u> The boundaries can cause a modification of the dynamics of a piping system (Azizpour, 2006) that can lead to gross underestimation of the seismic actions on piping elements;

- Methods of analysis. The use of pseudo—static analysis for the seismic verifications of piping elements can be acceptable if the input acceleration response spectra are defined with the Floor Response Spectra approach. In this case, the dynamic interaction between supporting structure and the pipe is not taken into account, but only in-structure spectra are used to model the dynamic amplification effect of the supporting structure. The Modal Response Spectrum method is an alternative approach that leads to the inclusion of the dynamic behavior of the piping elements. The modal results and directional results are combined to obtain a total, resultant response of the system. The analysis can be applied to the entire structure or only to the pipes. In the former case, in-structure spectra have to be used. Finally, linear or non-linear time history analyses can be used in order to increase the accuracy of the definition of the seismic actions in the piping elements as well as the actions on the supports.
- Application of Performance Based Earthquake Engineering approaches. The usual way of designing piping systems is based on the allowable stress approach. This means that the structure is considered elastic. Conversely, the modern approach to the seismic design of structures is to differentiate serviceability from ultimate limit states. This produces a high level of conservatism that seems to be in contrast with the modern Performance-Base design approach.

  The accurate definition and quantification of limit states for the application of modern seismic design approaches, e.g. LRFD, Performance-Based design, are then required. Indications for the Performance Based design of piping systems can be found in Bursi et al (2016).
- Coupling between piping and main components (e.g. tanks, vessels). The failure of the piping system connected to the tanks is one of the most common causes of loss of dangerous content during earthquakes. These types of failure can be avoided protecting brittle elements such as the valves of the piping system and providing sufficient flexibility in other elements of the system. Some indications on the effects of the interaction between piping systems and main items are reported in Bursi et al. (2014) and Bursi et al (2015).

  Additional suggestions and practical indications are presented in detail in ASCE, (2011). These refers in particular to the piping-tanks connections and briefly summarized in the figures below.

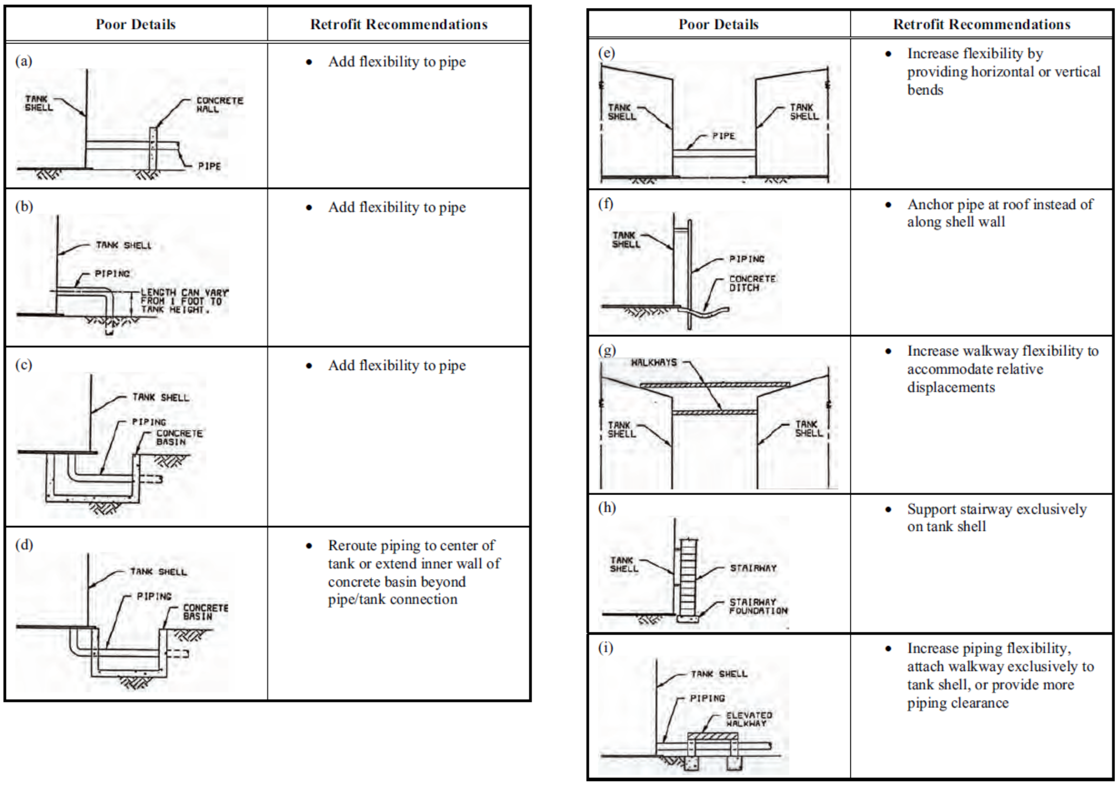

Figure 4-1: Recommendations for piping-tanks connections (ASCE, 2011)

- Piping should not pass directly with little or no flexibility from the tank shell or tank bottom to the ground or to rigid concrete walls, basins, pumps rigidly fixed to the ground. Indeed, in the first three cases additional piping flexibility should be provided by adding horizontal or vertical bends, or by installing a length of flexible piping. In the fourth case, piping should be rerouted to the center of the tank or, if the piping is flexible enough, the concrete basin may be extended beyond the pipe/tank connection. Similar preventions should be adopted also for connecting two tanks. Summarizing, rigid piping connected to tanks shall be avoided to prevent seismic failures.
- Connections along the tank shell should be avoided and replaced by a connection near the shell/roof intersection, coupled with sliding connections or “guides” along the shell wall.
- Roof access is frequently facilitated by walkways spanning between the tanks. It is important to increase walkways flexibility in order to accommodate relative displacement between tanks avoiding punching of the tank shells. In addition, it is suggested to avoid as much as possible the positioning of walkways between the external walls of the tanks to prevent shell rupture and release of products. It is suggested to position upper walkways that in case of failure whereas failure would likely only lead to a release of fumes and a much lower level of economic loss.
- Stairways should not be attached to both the tank shells and the foundation;

4.3.2 Retrofit of Existing Structures

Retrofit measure for existing piping systems are not yet completely studied. Here below some indications for potential benefit measures are reported.

- Modifications applied to the boundary conditions. As already presented for new structures, all the modifications to the boundary conditions can be easily applied to the existing piping systems: increment of points with shear resistance, or in contrary, increment of points with sliding characteristics, reduction of the coupling between different elements by adding expansion joints in adequate locations, substitution of rigid connection with flexible connections.
- Passive and active control techniques applied to the supported structure. A variety of active and passive control techniques/devices can be used for seismic response mitigation of pipelines (see e.g. Paolacci et al., 2013; Reza et al., 2014). A variety of passive devices have been proposed for the structural response of piping systems including the viscoelastic damper, the compact dynamic absorber, friction damper and X-plate damper (XPD) (Bakre et al, 2006; Kelly, 1980; Kunieda et al, 1987; Shimuzu et al, 1996). An alternative solution consists in using steel cable dampers (Wire-Ropes). This device allows for thermal expansion associated with piping systems, but restrains the pipe to prevent large dynamic deflections. The device acts as an energy absorbing dashpot in six degrees of freedom utilizing sliding friction between the strands composing the Wire-Rope (WR).
- Passive and active control techniques applied to the supporting structures. Supporting frames can be effectively protected by several control techniques. For example, to reduce forces and displacements, dissipative bracings and dissipative coupling techniques can be profitably used, similar to slim vessels. To avoid damage in the supported equipment (compressors, pumps, tanks, etc), the TMD technique can also be adopted. In fact, an effective way to protect seismic vulnerable equipment consists in implementing an isolation system between the internal apparatus and the supporting structure.

5 FLOODING VULNERABILITY

The present paragraphs report considerations related to the flooding vulnerability of petrochemical tanks, horizontal pressure vessels, vertical pressure vessels and piping. The typical damages observed in petrochemical plants are floatation of the items, shell buckling of tanks and vessels, rigid sliding of the items. These are the so called "short terms damages" but there are also the "long terms damages" mainly related to the chemical and biological effects of the water inside the petrochemical plants. The following figure shows this concept in a qualitative form.

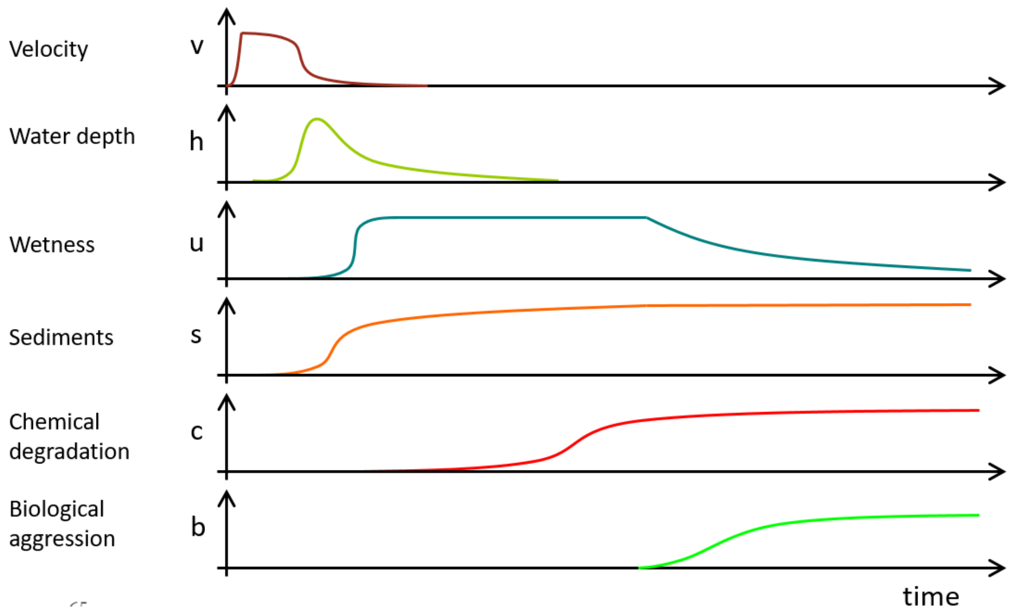

Figure 5-1: Temporal evolution of the damage after a flood event

The main risk mitigation measures to be applied in the design/construction and retrofit of petrochemical plants are hence referred to mitigate the probability of occurrence of the previous damages and to mitigate their consequences. The following list provides indications of such potential measures:

- Avoid the use of unanchored items. Although the specifications for the anchorage of storage tanks have been given in current standards (e.g., API, 620, 650), the common design practice in many plants is still based on self-anchored storage tanks (Godoy, 2007). Nevertheless, anchorage of storage tanks can significantly reduce or even eliminate the risk of flotation (Khakzad and van Gelder, 2017).
- Consideration of the buoyancy force due to flooding in the definition of the connection properties;
- Consideration of all the possible scenarios of item weights in the calculation of the buoyancy force. Khakzad and van Gelder (2017) showed that, regardless of the size of storage tanks and the type of their chemical inventory, a minimum height of chemicals inside the storage tank equal to the inundation height of the expected flood would be sufficient to prevent from floatation.

- Based on field observations after hurricanes, sell-buckling failure mode of atmospheric storage tanks has mainly been due to strong winds or impact of waterborne debris (Godoy, 2007). Nevertheless, strengthening the shell via increasing the shell thickness and application of ring stiffeners would to a large scale prevent from such failure mode, especially in case of wind-driven shell buckling.
- Levees, Floodwalls, Seawalls, and other appurtenant structures. These structures are designed to prevent floodwaters and storm surges from reaching areas that are at risk. Consequences of failure can be catastrophic because those behind the structure can be subject to rapid inundation and flooding conditions more severe than if the floodwaters had risen gradually;
- Floodways, Spillways, and Channels. Floodways, spillways, and channels are constructed to carry floodwaters around a region where the capacity of a river to pass a large volume of floodwaters past a critical location is limited. Under some circumstances, river channels can be modified to increase their flood carrying capacity;
- Structure Elevation. By raising a structure, tanks or vessels, above the expected flood level, flood damages can be prevented. However, placing the storage tanks and vessels of large chemical inventory on elevated ground may give rise to other types of accident scenarios which need to be taken into account. For instance, in case of spillage from an elevated storage tank without presence of flood, the released chemicals are likely to flow towards other process units and ignition sources in the vicinity, posing a major risk of fire/explosion and thus triggering domino effect scenarios.

More details about the risk analysis for flooding are reported in Kelman, (2004), Apel et al (2009), Merz et al (2010), Jonkman et al (2008), McDonnell (2003), Merz et al (2010), Cozzani et al. (2010), and Khakzad and van Gelder (2017, 2018), among others.

6 MAN-MADE VULNERABILITY

The vulnerability of the petrochemical plants with respect to man-made hazards can be reduced, in general, with the following main actions:

- Plant redundancy: in case of occurrence of an hazardous scenario caused by an operator error, this action has the aim to reduce the domino effect due to a potential damage in one point of the plant;
- Increase the level of maintenance of all the items included in the petrochemical plants with particular regard to those with the large amount of hazardous materials. This will ensure a good answer of the machine and equipment to a possible operator error and alert him/her in case of process deviation;
- Facilitate the confinement of hazardous materials in order to reduce the effect of their leakage;
- Control the leaks (emergency blocking, facilitate dispersion, etc.);
- Defend against the consequences of leaks (fire protection systems, explosion-resistant buildings, etc.).

- Develop dedicated Plant Security Plan (in case of sabotage or terrorism) and Emergency Evacuation Plan (in case of major hazard) identifying the zones of concerns around the plant.
- Physical Security Enhancement. The most common approach to improving site security is to "harden" defences so that sites would be less vulnerable to terrorists. An effective protection system serves three functions: detection (discovery or sensing of adversary action), delay (impediment to adversary progress), and response by security personnel to ensure that a threat is neutralized. Examples of hardening tactics include increasing security patrols, strengthening fences, installing better locks on doors, relocating sensitive chemical processes within the facility, installing intruder detection systems and alarms, and performing background checks on employees.
- Technology Assessment and Inherently Safer Options. An alternative strategy for reducing risk is advocated by environmental groups. It would reduce the hazardous characteristics of the facility, for example, by reducing production, processing, storage, and use of dangerous chemicals, or changing the characteristics of chemicals to make them less dangerous (e.g., by reducing volatility). Such tactics aim to improve the "inherent safety" of a site
- Deterrence. A third approach to reducing risks aims to reduce theft, rather than direct attacks, by making dangerous chemicals in use at a facility less attractive to criminals, for example, by introducing a colour or other property that facilitates detection and tracking by authorities (so-called "taggants"), or by creating and storing antidotes to toxic effects.
- Restricted Access to Information. Restricting terrorists' access to information about vulnerability and location of chemical facilities also might reduce the risk of terrorism.

7 QUALITATIVE COST-BENEFIT ANALYSIS

The previous risk mitigation indications relative to the reduction of the vulnerability with respect to different hazards are collected in a synoptic table in order to develop a qualitative value engineering of all the options. This has the aim to guide the engineers and the possible stakeholder to the pros and cons of the different options. With respect to the reduction of vulnerability, the different items are characterised with low/medium/high vulnerability reduction depending on the expected effect of the applications of each item.

				REDUCTION LOW/MEDIUM/HIGH	CONS
SEISMIC VULNERABILITY	TANKS	Design/Construction	Design performed with modern specific seismic codes (Eurocode 8, ASCE7, New Zealand code)	High	*n.a.*
			Consideration of Soil Structure Interaction	Medium	Increment of the Design Cost because particular design skills are required
			Increase Freeboard height	Medium	Increment of the construction cost because of the reduction of the volume capacity
			Installation of Seismic Isolators	High	Increment of the installation cost but possibly lower than deep foundations or soil improvement solutions. Increment of the design cost Increment of the maintenance cost
			Use of Fluid Viscous Dampers	High	Increment of the installation cost but possibly lower than deep foundations or soil improvement solutions. Increment of the design cost Increment of the maintenance cost
			Installation of flexible pipe-tanks joints	Medium	Increment of the construction cost
			Avoid uplift and tension forces at the base	Medium	*n.a.*
			Detailing of the anchor bolts	Medium	*n.a.*
		Retrofit	Strengthening of the base connections	High	Increment of the installation cost
			Strengthening of the tank walls	High	Increment of the installation cost
			Substitution of the tank to pipe connections	Medium	Increment of the installation cost
			Installation of Seismic Isolators	High	Increment of the installation cost
	VESSELS	Design/Construction	Horizontal Vessels - Detailed consideration of the base connections	Medium	*n.a.*
			Horizontal Vessels - Capacity Design Considerations	Medium	*n.a.*
			Horizontal Vessels- Inclusion of Soil structure Interaction	Low	Increment of the Design Cost because particular design skills are required
			Horizontal Vessels - Consideration of local bending and buckling of the saddle supports	Medium	*n.a.*
			Horizontal Vessels - Consideration of reinforcing rings	Low	*n.a.*
			Vertical Vessels - Design considerations for the connections	Medium	*n.a.*
			Vertical Vessels- Design Considerations for the skirt	Medium	*n.a.*
			Vertical Vessels-Capacity Design	Medium	*n.a.*
			Vertical Vessels - Appropriate FEM Modeling to capture the actual natural period and subsequentely the seismic actions.	Medium	Increment of the Design Cost because particular design skills are required
		Retrofit	Replace the rigid pipe/vessels connections with flexible connections;	Medium	Increment of the construction cost
			Strengthening of the vessel wall base and skirt especially for vertical vessels;	Medium	Increment of the installation cost
			Strengthening of the base connections and increment of their energy dissipation capacity;	Medium	Increment of the installation cost
			Base isolation	High	Increment of the installation cost Increment of the Maintenance cost
			Passive control techniques	High	Increment of the installation cost Increment of the Maintenance cost
	PIPING	Design/Construction	Accurate consideration of the piping mass in the design phase	Low	Increment of the Design Cost because particular design skills are required
			Accurate definition of the elbows and fittings in the design phase	Low	Increment of the Design Cost because particular design skills are required
			Coupling effect between supported (piping) and supporting elements (pipe rack).	Medium	Increment of the Design Cost because particular design skills are required
			Accurate consideration of the stiffness of the boundary conditions.	Medium	Increment of the Design Cost because particular design skills are required
			Methods of analysis	Medium	Increment of the Design Cost because particular design skills are required
			Application of Performance Based Earthquake Engineering approaches	Medium	Increment of the Design Cost because particular design skills are required
			Coupling between piping and main components (e.g. tanks, vessels).	Medium	Increment of the Design Cost because particular design skills are required
		Retrofit	Modifications applied to the boundary conditions	Medium	Increment of the construction cost
			Passive and active control techniques applied to the supported structure.	High	Increment of the construction cost
			Passive and active control techniques applied to the supporting structures	High	Increment of the construction cost
FLOODING VULNERABILITY			Avoid the use of unanchored items	High	*n.a.*
			Consideration of the buoyancy force due to flooding in the definition of the connection properties	Medium	*n.a.*
			Consideration of all the possible scenarios of item weights in the calculation of the buoyancy force	Medium	Increment of the Design Cost because particular design skills are required
			Levees, Floodwalls, Seawalls, and other appurtenant structures designed to prevent floodwaters and storm surges from reaching areas that are at risk	High	Increment of the construction cost
			Floodways, Spillways, and Channels	High	Increment of the construction cost
			Structure Elevation. By raising a structure, tanks or vessels, above the expected flood level, flood damages can be prevented	High	Increment of the construction cost
MAN-MADE VULNERABILITY			Plant redundancy: this action has the aim to reduce the domino effect	Medium	Increment of the construction cost
			Developing a strong operational safety culture in facilities	High	*n.a.*
			Enhance the level of preparedness of the employees and of the managers	High	*n.a.*
			Increase the level of maintenance of all the items included in the petrochemical plants	Medium	Increment of the maintenance cost
			Facilitate the confinement of hazardous materials in order to reduce the effect of their leakage	Medium	Increment of the construction cost
			Control the leaks (emergency blocking, facilitate dispersion, etc.)	Medium	Increment of the construction cost
			Defend against the consequences of leaks (fire protection systems, explosion-resistant structures, etc.)	High	Increment of the construction cost

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8 CONCLUSIONS

In order to develop a practical guide for designers related to the multi-hazard risk reduction of new and existing industrial equipment, mainly tanks, vessels and piping, a table with the main indications collected in this report is presented below with indications for hazard, exposure and vulnerability.

Table 2 Summary of the Guidelines

HAZARD	***SEISMIC***	Include in the Seismic Hazard definition of ground shaking, ground deformations or ground failure caused by fault rupture, liquefaction and landslides, tsunamis
		Correct definition of the soil dynamic properties
		Avoid bad geotechnical locations (proximity to faults, cliff areas and subjected to possible liquefaction and close to stiff slopes)
		Definition of Site Specific Seismic spectra (with PSHA or DSHA)
		Avoid area located near to faults or near liquefiable soil
		Avoid site with steep slopes with potential stability problems
		Development of Site Response Analysis
	FLOOD	Cover all the potential natural events such as river flooding, dam breaks, coastal storm surges. Domino effect shall be included in the analysis;
		Cover all the aspects that may affect the flooding risk: meteo forecasting, hydrological model and hydraulic model;
		Accurate hydrological model and use of Physically Based Models (TOPKAPI, TUFLOW)
		Anchorage of storage tanks and process vessels can significantly reduce/eliminate the risk of floatation. This is particularly important for atmospheric storage tanks, which are usually self-anchored in practice.
		In case of imminent floods at the chemical plant, the empty storage tanks should be filled with water, or the height of chemicals inside non-empty storage tanks should be maintained at least equally to the inundation height of expected floods.
		Increasing the shell thickness of storage tanks and vessels as well as using ring stiffeners can reduce/prevent from shell buckling.
	MAN-MADE	Quantitative identification of all the hazards: errors in design, construction, maintenance; not voluntary errors by plant operators; sabotage; terrorism. Checklists, Hazard Identification Study (HAZID) or the Hazard and Operability Analysis (HAZOP).
		Developing a strong operational safety culture (training and information of personnel)
		Enhance the level of preparedness of the employees and of the managers with respect to all the safety measures to be applied during design phases and normal operations

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EXPOSURE	Provide adequate distances between equipment to avoid Domino Effect
	Limit the dimension of the elements containing hazardous materials
	Consider redundancy in the connection between different equipment

SEISMIC VULNERABILITY	**TANKS**	**Design/ Construction**	Design performed with modern specific seismic codes (Eurocode 8, ASCE7, New Zealand code)
			Consideration of Soil Structure Interaction
			Increase Freeboard height
			Installation of Seismic Isolators
			Use of Fluid Viscous Dampers
			Installation of flexible pipe-tanks joints
			Avoid uplift and tension forces at the base
			Detailing of the anchor bolts
		Retrofit	Strengthening of the base connections
			Strengthening of the tank walls
			Substitution of the tank to pipe connections
			Installation of Seismic Isolators
	VESSELS	**Design/ Construction**	Horizontal Vessels - Detailed consideration of the base connections
			Horizontal Vessels - Capacity Design Considerations
			Horizontal Vessels- Inclusion of Soil structure Interaction
			Horizontal Vessels - Consideration of local bending and buckling of the saddle supports
			Horizontal Vessels - Consideration of reinforcing rings
			Vertical Vessels - Design considerations for the connections
			Vertical Vessels- Design Considerations for the skirt
			Vertical Vessels-Capacity Design
			Vertical Vessels - Appropriate Modelling to capture the actual natural period and subsequently the seismic actions.
		Retrofit	Replace the rigid pipe/vessels connections with flexible connections;
			Strengthening of the vessel wall base and skirt especially for vertical vessels;
			Strengthening of the base connections and increment of their energy dissipation capacity;
			Base isolation
			Passive control techniques
	PIPING	**Design/ Construction**	Accurate consideration of the piping mass in the design phase
			Accurate definition of the elbows and fittings in the design phase
			Coupling effect between supported (piping) and supporting elements (pipe rack).

			Accurate consideration of the stiffness of the boundary conditions.
			Methods of analysis
			Application of Performance Based Earthquake Engineering approaches
			Coupling between piping and main components (e.g. tanks, vessels).
		Retrofit	Modifications applied to the boundary conditions
			Passive and active control techniques applied to the supported structure.
			Passive and active control techniques applied to the supporting structures

FLOODING VULNERABILITY	Avoid the use of unanchored items
	Consideration of the buoyancy force due to flooding in the definition of the connection properties
	Consideration of all the possible scenarios of item weights in the calculation of the buoyancy force
	Levees, Floodwalls, Seawalls, and other appurtenant structures designed to prevent floodwaters and storm surges from reaching areas that are at risk
	Floodways, Spillways, and Channels
	Structure Elevation. By raising a structure, tanks or vessels, above the expected flood level, flood damages can be prevented
MAN-MADE VULNERABILITY	Plant redundancy: this action has the aim to reduce the domino effect
	Increase the level of maintenance of all the items included in the petrochemical plants
	Facilitate the confinement of hazardous materials in order to reduce the effect of their leakage
	Control the leaks (emergency blocking, facilitate dispersion, etc.)
	Defend against the consequences of leaks (fire protection systems, explosion-resistant structures, etc.)
	Develop dedicated Plant Security Plan (in case of sabotage or terrorism) and Emergency Evacuation Plan (in case of major hazard)
	Physical Security Enhancement
	Technology Assessment and Inherently Safer Options
	Deterrence.
	Restricted Access to Information

In general, the risk of the petrochemical plants can be reduced with the use of advanced hazard forecasting methods, early warning systems and accurate emergency plans. In addition to this, risk mapping and risk prioritization should be overlapped to the local situation of a specific plant in order to address the potential risks. Finally, a multi hazard risk approach, has the one proposed in the project PEC, should be used with the aim to take into consideration all the sources of hazard in a quantitative form and to obtain uniform results for all the possible sources of hazards. This approach will lead to a better understanding of the risk of all the stakeholders involved.

Concerning the seismic risk, it can be observed that damages due to seismic events can be significantly reduced thanks to the applications of modern seismic codes available for practicing engineers. For piping systems, the knowledge of the seismic behaviour of coupled piping/frame systems is still at a research level and practical guidelines are still under development. Furthermore, seismic design of piping systems in the industry is not yet at the same level of understanding as for other equipment and the piping design is still mainly governed by functional requirements (pressure, temperature, maintenance, etc.). With this regards, Performance Based Engineering approaches and Quantitative Seismic Risk Analysis techniques appear to be promising especially for the seismic characterisation of existing facilities.

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