A framework for NaTech seismic risk assessment in industrial plants

Bernardino Chiaia and Valerio De Biagi*
Department of Structural, Geotechnical and Building Engineering,
Politecnico di Torino,
Corso Duca degli Abruzzi 24, Torino, 10129, Italy
Email: bernardino.chiaia@polito.it
Email: valerio.debiagi@polito.it
*Corresponding author

Cristina Zannini Quirini
ARCOS Engineering,
Corso Einaudi 18, Torino, 10129, Italy
Email: cristina.zannini@arcos-engineering.it

Luca Fiorentini
TECSA Srl,
ViaFigino 101, Pero (MI), 20016, Italy
Email: luca.fiorentini@tecsasrl.it

Vinicio Rossini and Piera Maria Carli
EOS-Evolution of Safety Srl,
Piazza della Vittoria 1, Lainate (MI), 20020, Italy
Email: vinicio.rossini@eoshse.com
Email: pieramaria.carli@eoshse.com

Abstract: In industrial districts, NaTech events are the causes of relevant accidents. The effects of the release of hazardous substances, the costs involved for rescue and chemical reclamation of ground and groundwater and the economical loss for the company may be enormous if one of such natural and technological events would happen. In order to identify those industrial items for which the seismic risk is high, a new approach based on a census data sheet and multi-criteria analysis taking into account both structural behaviour and industrial hazard is presented. The paper focuses the attention on the vulnerability analysis on refinery items, such as oil storage tanks and reactors/distillation towers.

Keywords: risk analysis; seismic hazard; NaTech events; refinery; industrial items.

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Biographical notes: Bernardino Chiaia obtained graduation in Civil Engineering at Politecnico di Bari in 1991 and a PhD in Structural Engineering in 1995. From 2002 he is Full Professor in Structural Engineering at Politecnico di Torino where he currently holds the position of Vice-Rector for International Affairs. He is author of 190 scientific publications on subjects of structural engineering, materials engineering and fracture mechanics. In 2004 he was one of the founders of the consultancy firm ARCOS Engineering in Torino (Italy). Now he is member of the Board of the firm.

Valerio De Biagi obtained graduation in Civil Engineering at Politecnico di Torino in 2008. From 2008 to 2010 he worked as structural engineer in Tecnoservices VdA. He has worked at Politecnico di Torino since 2011. In 2013, he discussed his PhD with a thesis on robustness of structures against extreme events. He is author of more than 45 scientific publications and his current research focuses on structural robustness and natural hazards.

Cristina Zannini Quirini obtained graduation in Architecture at Politecnico di Torino. She is manager of the consulting firm ARCOS Engineering, which offers services for civil engineering. She is an expert in structural engineering, seismic engineering, monitoring techniques and forensic engineering.

Luca Fiorentini is an expert in advanced thermo-fluidodynamics simulations and he is member of many association such NFPA, for which he is an expert of the technical commission on ‘Fire Risk Assessment Methods’, SFPE, FPA, IAFSS, AIChE, NAFI, IAAI and ESRA. He is author of various scientific publications and books on risk assessment. He is an analyst in the fields of environmental engineering, industrial engineering, fire safety engineering and forensic engineering at Tecsa srl.

Vinicio Rossini graduated in Industrial Chemistry in Bergamo (Italy) in 1975. From 1977 to 1985 he lived in Venezuela where he practised operating activities and technical consultancy in the oil industry. Since 1986 he has carried out risk analyses in the field of major accidents hazards, environmental impact assessments, fire engineering and trainer on industrial risks. From 2002 to February 2015 he was director of Tecsa srl. Currently, he is co-founder and director of EOS-Evolution of Safety Srl.

Piera Maria Carli obtained graduation in Chemical Engineering at Politecnico di Torino in 1997. From Sept 1997 to Feb 2015 she was an analyst in the fields of major accidents hazard, environmental impact assessments and fire engineering at Tecsa srl, becoming in charge of these sectors in 2002. Currently, she is co-founder and director of EOS-Evolution of Safety Srl.

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1 Introduction

NaTech events, like earthquakes, flooding, tornadoes and lightning represent major causes of relevant accidents in industrial plants. The combination of natural and technological features often leads to serious danger scenarios and therefore it must be properly investigated (see, e.g., triggering of big fires due to lightning). In Italy, there is a
high number of so-called RIR industrial plants settled in correspondence of sites with a medium or high seismic hazard. Their specific industrial processes, coupled with the presence of significant quantities of dangerous substances, imply that there is a strong concern for the consequence of accidents both at the level of the safety of human lives and infrastructures and at the level of environment preservation.

Among these sites, the oil and gas refineries and deposits are located throughout the Italian territory and play also a strategic role in the overall national energy supply program. Therefore, the assessment of the seismic vulnerability of oil tanks, LNG vessels and of process items (like, e.g., cracking columns, reactors, desalters and chimneys) represents a crucial task. A new methodology, developed in strict collaboration with ENI Spa and based on a 3-stages protocol, is described in this paper. A simple flowchart illustrating the novel methodology is proposed in Figure 1.

Due to the wide number of items, the first activity (Stage 1) is represented by the selection of the items to be analysed on the basis of their risk exposure. This can be carried through classical indexes methods, considering the nature and quantity of the hold-up (related, e.g., to inflammability and environment danger), the specific process, the plant layout and the possible activation of domino effects.

In the second stage, a simplified structural analysis is carried for the selected items. Normally, the API650 code is used in the case of tanks whereas the Italian and European building codes (Italian Republic, 2008a; European Committee for Standardization, 2006a; European Committee for Standardization, 2006b) are adopted for process items and chimneys. The seismic loads are obtained through linear dynamic analyses on simplified structural models, assuming conservative values whenever a direct knowledge of some mechanical quantity is not available. Then, the state of stress and some critical displacement are computed at significant points (e.g., piping connections, anchorages) and an estimate of vulnerability is obtained. Combining this value with the seismic hazard and with the quantified potential for loss that might occur as a result of an accident, a first quantification of the seismic risk is obtained for each item.

The third and last stage includes the direct knowledge of materials (also through experimental tests) and detailed structural calculations (FEM models and nonlinear analyses) only for the items whose seismic risk is above a threshold value.

The paper relates to the first two steps previously illustrated and is organised as follows. In Section 2, a short description of NaTech scenarios and petrochemical facilities is made. The methodology is described in detail in Section 3. A simple application on the seismic verification of a petroleum tank is proposed in Section 4. The conclusions of the paper are reported in Section 5. We would like to precise that all the research work herein described relates to Italian industrial plants. Because of that, many reminds are to the Italian laws and code of practice.

2 NaTech events on industrial plants

2.1 Background

Natural disasters present a major source of risk that has direct effects on the constructions, that turn into danger for the occupants. In addition, in the case of industrial districts, they can involve accidental releases of hazardous substances from the plants and storage facilities affected by the disaster. In this case, the disaster acts as external cause
of failure of the production items. Such events have been denoted as NaTech events, indicating their dual composition: natural and technological (Showalter and Myers, 1994).

The interaction between natural disasters and industrial plants produces an increment of frequency and intensity of the accident scenarios generated by the release of hazardous substances. The geographical extent of the area affected by the same cataclysm plays an important role in the frequency of industrial releases (Krausmann and Mushtaq, 2008). An emergency created by a natural disaster, and the consequent release of dangerous materials, are under the responsibility of intervention and rescue organisations, to which a relative small amount of resources is assigned.

Figure 1  Flowchart of the proposed risk assessment procedure

In the last years a growing attention to the problems linked to NaTech events has been paid. Various research studies examine recent injurious events and the following effects on the environment, giving a framework for developing methods and strategies for risk management. In particular, in Young et al. (2004), a systematic review of hazardous and NaTech events is made. The frequency of direct and indirect releases of dangerous substances is shown.
Specific procedures for the quantitative assessment of the NaTech risk related to earthquakes and floods have been developed recently both using QRA methods and on the basis of an extensive research work concerning NaTech events (Antonioni et al., 2007; Antonioni et al., 2009; Campedel et al., 2008; Fabbrocino et al., 2005). The approach consists, first, on defining the characteristics of the natural phenomenon (on the basis of frequency and intensity). The potentially damaged items, the severity of the expected damage and the amount of potentially hazardous released substances are then identified. The vulnerability of each item, value of which derives from a large amount of observations using probabilistic methods, is fundamental in this step.

2.2 Refinery: set-up

2.2.1 Tanks for petroleum storage

A tank is composed by four parts. From the bottom to the top the foundation is found first. It is made of mechanically-compacted and stabilised ground. If necessary, foundation piles can be constructed. In case of low-temperature tank, in order to prevent freezing in the ground and in water-table, the container has to be put on a concrete slab lying on a suspended foundation where air can pass and prevent the low temperature to affect in the ground. For simplicity, the container, which contains oil products in our analysis, is made of steel. The bottom of the container is made of superposed and welded rectangular steel plates (usually 6 mm thick in the surveyed items). Sometimes, a thicker area, i.e., the so-called annular plates, may be required at the connection between the bottom of the tank and its vertical plates. The cylindrical shell is made of welded steel plates with thickness decreasing with height. The top of the roof can be either floating or fixed. In the former, i.e., floating roof, closed-top pontoon compartments are appended to metal plates lying directly on the liquid of the container. Various configurations are possible: single-deck pontoon floating roof if the pontoons cover the external periphery of the roof, double-deck floating roof is the entire roof is constructed of closed-top flotation compartments. Since the roof floats on the liquid, it moves upward and downward depending on the operations on the tank. The roof is kept in its position through a peripheral rim seal and anti-rotation guide poles. Rain accumulating on the roof is drained through a flexible pipe. In fixed roof tanks, the top is made of steel plates with independent supporting system (structural shapes or small trusses) which are vertically supported either by the shell of the tank or by independent internal columns. Floating roofs are typical in the storage of gasoline. This hydrocarbon has a high volatile part and, thus, any air chamber filled by vapours would be potentially explosive. Fixed roofs are suitable for the storage of diesel products, since no volatile part is present. It may happen that both floating and fixed roofs are present. For operations and inspections, auxiliary attachments are present (e.g., staircases, manholes). Piping and connections, usually at the base of the item are present. In order to prevent the leaking of oil product, the tank is put into a large containment basin made of compacted ground or concrete.

For the storage of gas products, the extensively used container is represented by a spherical pressure vessel supported on circumferentially spaced columns, i.e., the so-called “Hortonsphere”, or “Horton” sphere, from its inventor, G. Horton (1924). The original shape has changed across the decades. The main innovation in the design was made by Horton. He found that these spherical tanks, when subjected to expansion and contraction caused by the heat of the sun, to changes in temperature caused by the weather, or to variations in internal pressure, loose from their supporting legs. That is
why he introduced circular hollow legs instead of section profile legs (Horton, 1947). The majority of vessels relates to this final configuration.

2.2.2 Items in refinery industry

Distillation is probably the most widely used separation process in the chemical industries; its applications ranging from the rectification of alcohol, which has been practiced since antiquity, to the fractionation of crude oil (Towler and Sinnott, 2012).

Without the conceit of being complete and detailed, we shortly describe a simple refinery process (crude distillation), which let us able to justify the presence of large and complex infrastructures in a refinery. Observing the process reported in Figure 2, first, the crude oil, which comes from the underground exploitation, is temporary stored into a tank (letter a in the sketch). After that, the crude oil is heated (b) and then water is added. In the so called desalter (c), the salt present into the crude is removed in the water (brine, i.e., water with NaCl). Avoiding this step, undesired salt deposition and corrosion would be present in the following reactors. The crude is then heated into a fired heater (d in Figure 2) and reaches a temperature of roughly 400°C before entering the fractional distillation tower (e). Here, different products condense at various temperatures. For example, fuel oil is collected at around 370°C, diesel at 300°C, kerosene at 200°C and petrol at 150°C (Leffler, 2008). Each of the previous cuts is sent to a stripper column (f in Figure 2) where the tails of the distillation are cut and the product is further refined. All the previous products are then temporarily stored into tanks (h) for further chemical operations or before distribution. The gasses collected at the top of the distillation tower are further cooled and the components (gas and light straight run gasoline, LSR) are separated in the reflux drum (g) and pumped to vessels in the deposit. The gaseous part is liquefied.

Despite simple, the previous description highlights the fact that, for the chemical process, a controlled cooling of vapours is needed. This is achieved through vertical reactors, i.e., the towers, into which the vapour raises and is collected and pumped to other refining steps. The fired heaters are made of external plates with an internal fire-resistant masonry layer into which a coil of finned-tube is present. Combustion smokes are throw out through a chimney on the top of the heater. It results that such items can reach heights up to 40-50 meters. Due to the complexity of the process and the high number of products piping is massive and connections and interferences between the various items are strongly present.

3 Risk assessment

In the framework of NaTech scenarios, any strategy for identifying in relatively short times those items to which a high risk is associated is kindly appreciated. Thus, we developed a framework for NaTech seismic risk assessment. The proposed approach accounts for the industrial risk, represented by the local danger due to the industrial process deriving from the use of the item, for the position of the item with respect to the seismic hazard, i.e., the local seismic excitation as well as the local amplification effects, for the structural vulnerability of the item, which depends on the dynamic response and on the strength of the elements. For a proper evaluation of the risk, additional aspects must be considered: the interaction between the structural elements and the industrial components, e.g., piping, connections, and so forth, and the material degradation due
to the chemical processes, that might indirectly affect the strength of the structural elements. In such a situation in which the vibrating structures are very close ones to each others, with many connections, the mutual effects between different items must be taken into account. In other words, a single structure, in vibrating, may impact a neighbouring one and cause damages on it (the so-called domino effect).

**Figure 2**  Simplified sketch of a crude oil distillation plant, from Gary et al. (2007). Details of the components are reported within the text (see online version for colours)

**Figure 3**  Example of the output of the census data sheet (see online version for colours)
The analysis is made through a census data sheet able to account both for industrial risk and structural behaviour, as depicted previously. The approach is not new in seismic engineering. Referring to ordinary building (with no industrial risks), for long time, post earthquake surveys in Italy have been carried out using vulnerability forms prepared by the National Group for the Defense against Earthquakes (GNDT). The used forms were conceived to determine vulnerability and detect damages without any specific concern for building usability. In the last two decades, a joint working group of the National Seismic Survey (SSN) and GNDT created a specific tool (AeDES) for damage assessment, short term countermeasures for damage limitation and evaluation of the post earthquake usability of ordinary buildings (Baggio et al., 2007). In addition, after 2002 Molise Earthquake (M 5.9) and the consequent collapse of the primary school of San Giuliano di Puglia located near the epicentre, where 28 dead, a wide risk assessment policy was planned in Italy. The Italian government imposed the census and the further seismic verification of those structures which collapse might be relevant (Italian Republic, 2008b). First, the attention was paid to schools and hospitals. In order to achieve such a large task, the Italian Civil Protection Department, i.e., the Italian institution that deals with the prediction, prevention and management of exceptional events, published three census data-sheets accounting for three different levels of detail in the evaluation of the seismic vulnerability of the building (L0, L1 and L2). These are available at http://rischiosismico.regione.marche.it/RISCHIO-SISMICO. An example of the output of the census data sheet is proposed in Figure 3.

Speaking about the industrial risk, the effects of damage are considered through simplified models, as detailed in Section 3.1. Taking the bases from the previous examples, from the structural point of view, the proposed risk assessment procedure is something more than a basic census data and less than a full seismic calculation. We deal with this topic in Sections 3.2 and 3.3.

3.1 Consequences

In any industrial plant, items and constructions are various and, usually, their amount is very large. An initial screening is necessary in order to limit the vulnerability analysis to those items that represent a potential source a NaTech hazard. The framework of our analysis is on petrochemical refineries. That is why, in the specific, the attention is put on three types of items/constructions: (i) those structures that are large or tall, e.g., chimneys, that, in collapsing, might damage other items which, in turn, may be critical in a NaTech scenario. In addition, the focus is posed on (ii) the structures and the buildings whose activity is fundamental in the management of the emergency, e.g., fireguards services, control rooms, first aid, and on (iii) the systems that are useful during and after the NaTech event, e.g., water supply, pumping stations, piping. Particular attention is paid to storage tanks, where the items are classified with respect to the toxicity of the stored substances. First, the focus must be put to those tanks which collapse may pollute underground water, depending on the drainage of the area. This is the case of tanks which containment basin has no pavement or adequate waterproof geotechnical solution (e.g., compacted clay). Similar attention is paid to pipe-ways throughout the refinery.

The danger represented by any damage on such items is evaluated through the procedure proposed in Seveso Directives. These aim at “preventing major accidents which involve dangerous substances, and to limit their consequences for man and the environment with a view to ensuring high levels of protection throughout the Community
in a consistent and effective manner” (Mitchison and Porter, 1998). The requirements of these regulations are usually met by an industrial facility through the creation and the implementation of safety reports (Cruz et al., 2004). We used these documents in the analysis of the consequences of the failure of each item. In this sense, the concept of relevant accident is fundamental for the understanding of the evaluation procedure. That is, such accident technically refers to the release of toxic substances that make people or environment in danger (either immediate or delayed). Following the prescriptions contained in the Italian regulations, the list of the potentially dangerous items has been made using the index method reported in DPCM 25/2/2005 (Italian Republic, 2005). This is one of the possible approaches for defining potentially dangerous activities in an industrial plant (Tixier et al., 2002). It considers the hold-up, the chemistry of the released substance and the damage distance. First, two risk areas are computed: one within the bounds of “true impact” and one within the bounds of “true damage”. Then the effects due to the release of the whole content of the considered item are evaluated; this gives a preliminary estimate of the risk associated to each item. In parallel, the presence of inhabited or protected areas and important infrastructures close to the refinery are considered in the analysis and in the selection of the items which structural vulnerability has to be evaluated.

3.2 Vulnerability

3.2.1 Tanks for petroleum storage

The estimation of the effects of future earthquakes on tanks is a key element in the measure of the vulnerability of refinery items because of various aspects. First, the content of the tank can be flammable or, in the worst case, can be explosive in case of sparks. This can engender major damages those in deposits that may be closed to inhabited areas.

The behaviour of such items under seismic excitation can be very peculiar. A singular kind of instability is observed in filled tanks: the so-called elephant-foot buckling, see for example Malhotra (1997) for details. Alternative causes of damages are represented by the yielding of the shell plates in tension and in compression and the excessive displacements of the container or the roof. Despite the stiffness of peripheral seals in floating roof tanks, the possibility of ignition due to friction between metallic parts is possible and can be the cause of fires. In slender tanks, if earthquake ground motion action is large, the possibility of tank overturning exists and can be prevented with anchorages in the foundation.

Sloshing of the liquid represents the driving action of the previously described damages. The sloshing is the seismic oscillation of a liquid into a container. The first studies on the analyses of the hydrodynamic forces were conducted in the 1940s in the USA by Housner (1963). Referring to tanks, Veletsos and colleagues (1977, 1984) set up a theoretical framework for the study and the design of tanks. At present, the problem of sloshing is studied theoretically (Ibrahim, 2005), numerically and experimentally.

In absence of seism, i.e., in static conditions, the weight of the mass of a liquid into a tank reduces to a triangular pressure distribution acting on the internal side of the container (hydrostatic pressure distribution). When the container is subjected to horizontal acceleration, the oscillation of the liquid mass determines a variation of the distribution of pressures. Various shapes are possible: Eurocode 8 (European Committee
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for Standardization, 2006c) proposes various expressions based on Bessel’s functions. American guidelines adopt alternative solutions of the problem (American Petroleum Institute, 2013; American Water Works Association, 1997). Each standardisation committee has formulated, in the past, various requirements on construction methods and verification of infrastructures or storage of petroleum and derivatives. The details given in the national documents are, in many respects, equivalent to each other (Hamdan, 2000).

As reported by Malhotra (1997), the forces acting on a tank are classified as impulsive (due to the inertia of the liquid close to the inside of the tank), and convective (due to the movement of the liquid mass, under the hypothesis of rigid lateral walls). The dynamic analysis of a liquid-filled tank may be carried out using the concept of generalised multi-degree-of-freedom (MDOF) systems accounting for both the impulsive and the convective modes of vibration of the tank-liquid system. For practical applications, only the first few modes of vibration need to be considered in the analysis. Systems with a unique concentrated mass are adopted only when the deformability of the tank is limited (e.g., in case of concrete tanks) and the liquid is not affected by sloshing (low level, low horizontal forces).

As observed in the surveyed deposits in Italy, the tanks date back to the second half of 20th Century and have been designed following American prescriptions. In 1961, the American Petroleum Institute (API) has emanated the Standard API 650 (American Petroleum Institute, 2013) for the design of new petrochemical storage systems. The document establishes minimum requirements for material, design, fabrication, erection and testing for vertical cylinders containing liquids (with some restriction on temperature and pressure) in order to provide to the industry adequate safety and reasonable economy in the storage of petroleum and petroleum products. In the late 80s, the API began the development of a new standard to address specific maintenance and inspection issues for existing aboveground storage tanks, i.e., the Standard API 653 (American Petroleum Institute, 2014; Lieb, 2001). In addition, for tanks containing products at low-pressure or low-temperature, the Institute emanated Standard API 620 (American Petroleum Institute, 2008).

In the Standard API 650, a set of rules for the design of petroleum storage tanks are given. These are expressed either through mathematical expressions or through charts. Standard API 653 indicates that similar rules can be applied to analyse and verify existing containers. Referring to the design of tanks in seismic areas, the Standard API 650 has a special part (i.e., Appendix E) devoted to this topic. As illustrated above, the lateral force due to the fluid in the reservoir is decomposed into two contributions, i.e., impulsive and convective forces. The relative importance of the two forces depends essentially on the configuration of the tank. Since the lateral component of the seismic forces is primary, large diameters with shallow liquid favour the appearance of convective forces. On the contrary, if liquid depth is greater than the diameter, the impulsive forces are predominant.

Vibration periods are different (less than one second for impulsive component, more than 2–3 seconds for convective component) and computed differently. Standard API 650 use closed form expressions for getting both the periods. The Standard API 650, in its seismic appendix, leads to determine the overturning possibility as well as the forces in the lateral walls due to both impulsive and convective mechanisms. If the stabilising component (made essentially by the portion of liquid close to the inside of the container as well as the weight of the tank) dominates, no anchorages are required. All the
calculations require the acceleration spectrum related to the Maximum Considered Earthquake (MCE), as detailed in the following section. The Standard API 650 requires the determination of 3 points of the spectrum: peak ground acceleration, acceleration at short periods (0.2 s), corresponding to the plateau in Italian regulations and at long ones (1 s). The damping ratio is considered equal to 5% for structures and 0.50% for liquid convection mass, as reported in Malhotra et al. (2000).

3.2.2 Items in refinery industry

The estimation of the effects of seism on refinery items might be a difficult exercise of structural mechanics and seismic engineering. It is important to note that such items were not designed to be seismically safe. In order to account for various structural shapes, the following solution was adopted. A simplified finite element model able to catch the general behaviour of the item is built. This intends to answer various issues such as the behaviour of the support of the metallic item (usually made of concrete beams, columns and plates), the behaviour of the foundation under seismic excitation, the behaviour of the mechanical connections between the base and the metallic parts into which the chemical process occurs, the displacements of the piping connections, and the adequacy of the connecting piping to seismic displacements. Meanwhile, the simplified model has to be able to account for various structural configurations of the item.

A first estimation of the principal dynamical parameters (such as first vibration period) is done by mean a combination of flexible and rigid beam structures. For example, referring to fractional distillation towers, the simplified models are reported in Figure 4. Reactors lying on a concrete basement are modelled as a variable cross section beam (the stiffness decreases with the height) with a roller at the base which is horizontally supported by an elastic spring. The stiffness of the spring is equal to the horizontal stiffness of the concrete structure. On the contrary, reactors lying directly on ground are modelled as a variable cross section cantilever.

Anyway, before realising any structural model of the item, many relevant aspects have to be considered. Referring to the towers, the first issue to be addressed is the distribution of weights across the height of the item. The shell of fractional distillation towers can weigh up to 1 MN and, in addition, a large amount of masses are added along the height, that can reach 40 m. Studying the chemical process, one easily understand that the upper part of the column is filled with a mixture of vapours and liquids falling from one tray to the other until an output pipe collects the product and carries it to other production stages.

In order to calibrate the simplified models, a more detailed analysis has been conducted and the followed approach is detailed. First, the geometry of the container (distillation tower, or similar in case of different item) is reproduced by means of “shell elements” to which a proper thickness is assigned. The weight of the internal components, such as the distillation trays, can be distributed on the lateral surface by a localised increasing of the density of the steel composing the container. Then, the fluid is modelled. Referring to the fluid on distillation trays, a localised increment of density of the shells is proposed. If sloshing is expected, the impulsive part of the fluid is modelled through an increase of density of the shell. The convective component is introduced into the discrete model by means of an inverted pendulum onto which the impulsive mass of the liquid is assigned. The inverted pendulum has to be tuned (by changing its size) in order to meet the theoretical convective period found, for example, by Malhotra and
colleagues (1997; 2000). If the item is supported by a concrete (or metallic) structure, the base and the connections between the upper and the lower part must be accurately modelled as well since they can be the cause of collapse. Sometimes, bolts are present. In other situations, rollers have been observed. The correct support conditions have to be inserted in the model in order to examine the overall structural behaviour. Finally, the seismic excitation input is considered and the dynamic analysis is performed. As detailed in the following paragraph, in the majority of cases, the items were designed following the US guidelines that deal with Limit States differently from the Eurocodes. The choice of the correct return period of the seismic action is crucial for a correct vulnerability analysis.

Figure 4 Preliminary models for the determination of the major dynamical parameters of a petrochemical reactor/distillation column (see online version for colours)

3.3 Exposure

The seismic action used as the input of the calculation procedure provided by the Standard API 650 is the one related to the “maximum earthquake”. In the USA three different kinds of maximum earthquake are determined: (i) the Maximum Considered Earthquake (MCE) is the largest earthquake (in terms of magnitude) that appears capable of occurring under the known tectonic framework for a specific fault or seismic source, as based from deterministic analyses on geologic and seismologic data. (ii) The Maximum Considered Earthquake (MDE) is the earthquake that is expected to produce the strongest level of ground motions. The MDE can be based on deterministic or probabilistic methods. (iii) the Maximum Considered Earthquake (MCE) is the one used in building codes to define the earthquake level of shaking that has 2% probability of exceedance in 50 years. The value of the MCE is determined probabilistically.
The Standard API 650 is calibrated for the USA, where the parameters of the acceleration for seismic assessment are provided by Standards like ASCE 7 (American Society of Civil Engineers, 2010), the National Earthquake Hazard Reduction Program (FEMA, 2009) or the USGS. In order to go beyond the previous documents, the American Petroleum Institute has implemented its Standard in such a way to be used in areas other than the territory of the USA. In reference to the current Italian law given in the “Norme Tecniche per le Costruzioni” (Italian Republic, 2008a), it is necessary to establish a design working life, the importance class and the class of use for each considered item.

Various choices can be made with respect to the design working life to consider. Trying to keep congruity with Standard API 650 (in case of tanks for storage of oil products), the following general considerations can be made. First, the choice of the value of the design working life of the item is not linked either to the importance of the construction, or to the class of use. The value of the design working life has two important values: the first, most obvious, is related to the durability of the item, i.e., the speed of corrosion, decay of materials and wear of any movable parts or non-mobile (both for chemical attack and atmospheric attack, or for mechanical fatigue due to vibrations). The second issue, specific for the NaTech events scenarios, is linked to the probability of occurrence of an event (earthquake) during the operating life of the tank. Obviously, a structure in operation for 100 years is more likely to experience a seismic event, characterised by a specific intensity compared to a construction in operation for 50 years. The weight of this inference is obviously linked to the seismic return period, which is variable and defined probabilistically;

For tanks design and verification, Standard API 650 considers shaking parameters from the Maximum Considered Earthquake, i.e., the earthquake whose probability of exceedance is equal to 2% in 50 years. This probabilistic statement corresponds to an event with return period equal to 2475 years (maximum return period for which the Italian “Norme Tecniche per le Costruzioni, 2008” provide spectrum parameters) as can be verified by the following expression:

$$1 - \left(1 - \frac{1}{2475}\right)^{50} = 0.02$$  \hspace{1cm} (1)

As far as the Italian law does not account exceedance probabilities of 2%, an earthquake with a return period equal to 2475 years is to be used in testing to limit state of collapse (5% probability of exceedance in the reference period) using a reference period of the seismic equal to 126 years, as expressed in the following relationship

$$1 - \left(1 - \frac{1}{2475}\right)^{126} = 0.05$$  \hspace{1cm} (2)

### 4 Example

In the following, two examples are reported. The first relates to a simplified seismic structural analysis on a large tank containing crude oil. The second example reports an advanced seismic structural analysis on a refinery reactor (a fractional distillation column).
4.1 Simplified seismic structural analysis of a tank for crude oil

The item is set in the proximity of a refinery and serves as a storage of raw material for the production of petroleum distillates. Following the approach proposed in Section 3.1, it results that the tank and its content are susceptible of NaTech hazard with an average hazard level.

Tank diameter and height are 88.52 m and 19.60 m, respectively; the capacity is about $1.2 \times 10^5$ cubic meters. The item dates back to the end of the Seventies, as reported on the design drawings. The thicknesses of all the shell plates and the bottom plates are indicated in the original drawings of the item. The design thicknesses of the plates are compared with the measured ones: it results that, in some measured points, due to the corrosion during the operation, the real plates are thinner than expected. The top of the tank is single-pontoon floating roof type. The material constituting the tank is evaluated from the design drawings.

Sometimes, design data are missing. In this sense, the thickness of the shell plates is assumed from the most recent survey. For the material, if not available, a common construction steel is supposed, i.e., EN 10025–S235JR.

The tank is set in a medium low seismic area, i.e., level III over a range of four in the Italian regulations (Italian Republic, 2008b). The peak ground acceleration on rocky soil related to 10% probability of exceedance over a period of 50 years is 0.073g. After other surveys in the surrounding area, it has found that the ground can be related to Ground Type B in European Committee for Standardization (2006c), i.e., deposits of very dense sand, gravel, or very stiff clay, at least several tens of meters in thickness, characterised by a gradual increase of mechanical properties with depth.

The vulnerability of the tank is evaluated through Standard API650 procedure, which are not reported herein for brevity (refer to American Petroleum Institute, 2013, Appendix E for the details). The geometry of the tank is determined from the original drawings. The thickness of each plate is taken as the minimum between the design and the measured value. The weight of the auxiliary attachments is evaluated in 30 kN. The input seismic action is computed after the three parameters of the spectrum given in Italian Republic (2008a) related to a seism with return period equal to 2450 years: the peak ground acceleration on rocky soil, $a_g = 0.117g$, the amplification factor, $F_0 = 2.747$, the period corresponding to the transition to constant velocity in the spectrum, $T_L = 0.438$. The entire spectrum is plotted, e.g., the one reported in black in Figure 5, for $\xi = 5\%$. The input seismic parameters in API650 are reported in the red boxes in Figure 5. $S_0=0.117g$ is the acceleration at a period of zero seconds; similarly, $S_1=0.219g$ is the acceleration at one second period. The acceleration corresponding to the plateau in the acceleration spectrum is denoted as $S_{SS}$, i.e., the acceleration at short periods (0.2 s), and $S_{SDS}$. The transition period $T_L$ is equal to $4a_g/g + 1.6 = 2.068$ s.

The following checks are made. The shear force at the base has to be smaller than the friction force due to the weight of the container and its content. The height sloshing wave in the tank must be relatively small. The stability of the tank under the seismic action is assessed through the anchorage ratio. In order not to be vulnerable, the anchorage ratio value proposed by American Petroleum Institute (2013) must satisfy the configuration of the tank. In other words, if specific anchorages are not present, the anchorage ratio has to
be smaller than 1.54. The stresses in compression (vertical direction) and in tension (tangential direction) are computed with the simplified expressions reported in American Petroleum Institute (2013). These must be smaller than the corresponding strength.

In addition, a visual survey of the item is mandatory. During the inspection, an evaluation of the degree of degradation of the item is made. Other than the presence of oxidation of the plates, the weldings, the floating roof, the presence of settlements and the condition of the containment basin are considered. If serious conditions are observed, the vulnerability evaluation might be significantly affected.

**Figure 5** Required seismic data in the input procedure for the calculations in API650 (see online version for colours)

4.2 Simplified seismic structural analysis of a fractional distillation column

A fractional distillation column set at the top of a concrete base is considered. A sketch of the item is proposed in Figure 6. Only few technical drawing of the lower concrete structure are available; the structure is made of a 8-meters tall concrete frame at the top of which a 1.2 metres-thick concrete plate is set. In detail, four corner columns (60 × 60 cm²) are present; the columns are connected by 30 × 60 cm² beams at mid-height. A cognitive survey devoted to the evaluation of the mechanical properties (strength) of the concrete and the amount of reinforcement bar in each element has been organised. The previous data allows to create a numerical model of the structure. Columns and beams are modelled as 1D elements, the top plate is simulated with plate FE elements.

The reactor weighs about 477.75 kN (as reported on the original mechanical drawings) and is rigidly bolted to the concrete plate. The metallic part of the distillation column can be imagined as a shell of revolution. The thickness of the shell progressively reduces from 20 mm to 10 mm with the height. The reactor is modelled as a revolution shell. The top and the bottom of the distillation columns are made of two hemiellipsoidal shells.
The real thicknesses and materials of the reactor are inputed in the model. A preliminary run of the simulation has given that the total weight of the simulated reactor is 374.88 kN. The discrepancy between the real value and the simulated one is due to the presence of distillation trays that have not been accurately modelled and to the various manholes in the reactor. Because of that, the specific weight of the steel, $\gamma$ was incremented from 78.5 kN/m$^3$ to 87.5 kN/m$^3$. In this sense, an increment of $\gamma$ increases the mass of the item and, meanwhile, preserves the stiffness of the components. This step is fundamental for getting the true seismic response. The mass of the hold-up of the reactor is about $5.56 \times 10^5$ kg (as given by the technical direction of the refinery) and has density of 715 kg/m$^3$, i.e., a volume of 70.853 m$^3$; 12.723 m$^3$ are contained in the lower hemiellipsoidal shell, the remaining (58.130 m$^3$) fills the cylindrical part of the reactor (of internal diameter $D = 4.5$ m) up to an height $H = 3.65$ m. This mass can experience sloshing during earthquake. The sloshing mass is computed as $m = 58.130 \times 715 = 41563$ kg. The total mass, $m$, is separated into impulsive and convective components. The ratio of the impulsive component of the mass, $m_0$, to the total mass is evaluated following American Petroleum Institute (2013)

$$\frac{m_0}{m} = 1 - 0.218 \frac{D}{H} = 0.7323.$$  \hfill (3)

The centroid of the impulsive mass (equal to 30436 kg) is set at

$$h_0 = \left(0.50 - 0.094 \frac{D}{H}\right)H = 1.405\text{m}$$ \hfill (4)
from the bottom of the cylindrical part of the reactor. In the numerical model, the
impulsive mass is simulated incrementing the specific weight of the shell up to a height
of \(2h_0\). The ratio of the convective component of the mass of the first mode of sloshing,
\(m_1\), to the total mass is

\[
\frac{m_1}{m} = \frac{1}{4} \sqrt{\frac{27}{32}} \frac{D}{H} \tanh \left( \sqrt{\frac{27}{2}} \frac{H}{D} \right) = 0.2805
\]

(5)

The centroid of \(m_1 = 11658\) kg is set at

\[
h_c = \left[ 1 - \frac{\cosh \left( \frac{\sqrt{27} H}{2 \pi} \right) - 1}{\frac{\sqrt{27} H}{2 \pi} \sinh \left( \frac{\sqrt{27} H}{2 \pi} \right)} \right] H = 2.550m
\]

(6)

from the bottom of the cylindrical part of the reactor. The angular velocity of the first
mode of sloshing, \(\omega_1\), is

\[
\omega_1 = \sqrt{\frac{\lambda_1 \tanh \left( \frac{2A H}{D} \right)}{\frac{D}{2 \pi}}}
\]

(7)

where \(\lambda_1 = 1.8412\) is the zero of the first derivative Bessel function of the first kind, \(g\) is
the acceleration of gravity. It is \(\omega_1 = 2.8262\) s\(^{-1}\); thus, the period of the first mode of
sloshing is \(T_1 = 2.22\) s. The convective moving mass is simulated by adding a point mass
\((m_1)\) at the top of a vertical bar of length \(H_0\). The inverted pendulum is tuned by varying
the stiffness of the vertical bar in order to vibrate at 2.22 s.

The numerical analysis of the FE model gives the modes of vibration of the item. The
first mode is related to the sloshing, as expected, and it not shown herein. The first mode
of the whole item is translational and has a period of 0.47 seconds. The deformed shape
is illustrated in Figure 7(a). A diagonal translation is shown: this is due to the presence of
a metallic tower, supporting the piping, which is fixed to the concrete structure and is not
sketched for sake of simplicity. The second vibration mode is torsional and has a period
of 0.28 seconds, see Figure 7(b).

Figure 7 Sketch of the proposed distillation column (see online version for colours)
The structural safety of the concrete frame structure and the connections between the upper slab and the reactor are assessed following the common seismic design approaches at collapse limit state (Italian Republic, 2008a; Italian Republic, 2008b; European Committee for Standardization, 2006a; European Committee for Standardization, 2006b; European Committee for Standardization, 2006c). In general, it results that the connecting bolts are able to resist to the coupled shear-traction force, while the concrete frame fails because the lack of ductility of the horizontal beams. In addition, the heavy masses in elevation and the small size in plan of the item imply that the columns are in traction when the reactor experience an horizontal seismic force.

5 Conclusions

Damage scenarios due to NaTech events might interest the industrial districts and the surrounding areas. Due to the massive presence of chemical components, which may be toxic both for the environment and for the human life, the recovery costs and the social costs are large. In this framework, a risk assessment is necessary. In the paper, the attention was paid to the potential damages in refineries and petroleum products deposits triggered by a seismic excitation. The proposed approach consists in three phases. In a refinery, the number of items is very large. The first step in the proposed framework relates to the choice of the items to be further analysed in detail. This screening is essentially made on the bases of the chemical and industrial relevance of the item. Following that, the seismic vulnerability is determined. The vulnerability is determined through the estimation of the behaviour of the item under the seism and the comparison with threshold values. In considering the tanks for oil storage, it is possible to get an accurate estimate of mechanical properties of the structure constituting the item, e.g., vibration periods, stresses in material. In other cases, for example referring to distillation towers, simplified structural models able to catch the main behaviour of the item must be conceived and properly calibrated. In both the previous cases, a first quantification of the seismic risk is obtained combining the behaviour of the item and the seismic hazard in the area. Once the list of the vulnerable items is made, the lasting stage consists on an accurate structural investigation (material, experimental tests) and a detailed modelling (FEM models and nonlinear analyses) aimed at determining a precise estimate of the behaviour of the item under seism and at evaluating possible structural works for increasing the capacity under earthquake. The framework herein proposed has been implemented on a spreadsheet format. It allowed the evaluation of the NaTech seismic risk of more than 250 items across Italy (tanks and refinery items).

References


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