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# Analysis of the Seismic Risk of Major-Hazard Industrial Plants and Applicability of Innovative Seismic Protection Systems

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## 1. Introduction

Industrial plants are complex systems and it is such a complexity, due to numerous connections, equipment and components, together with the complexity of their operations that makes them particularly vulnerable (local vulnerability) to earthquakes (see Figure 1a).


Fig. 1. (a) Areal view of a refinery, (b) Damage in a process furnace (Izmit, 1999).

Activities carried out in process plants can also be arranged in series, which means that process activities are realized with specific sequence and boundary conditions. Consequently, the "failure" of a single element can get out of order the entire system. This is of fundamental importance for the seismic vulnerability of a plant (general vulnerability).

Seismic action can cause serious accidents to industrial plants as shown in several occasions. The actual worldwide situation of major-hazard plants against earthquakes should be considered as critical. For instance, in Italy about 30% of industrial plants with major-accident hazards are located in areas with a high seismic risk. In addition, in case of a seismic event, the earthquake can induce the simultaneous damage of different apparatus, whose effects can be amplified because of the failure of safety systems or the simultaneous generation of multiple accidental chains.

A representative example is certainly the Izmit Earthquake in Turkey (Erdik and Durukal, 2000), which induced severe damages to Tupras refinery (area of the plant, farm tanks, and landing place). An example of domino effect caused by a structural collapse was the breakdown of a concrete chimney that caused a big release of dangerous substances and damages to surrounding equipment (see Figure 1b).

In a plant, an earthquake can cause many dead as consequence of components collapses, similarly to what happens to buildings; moreover, the consequences deriving from a seismic event, such as economic losses for interruption of the production, environmental damages due to releases of dangerous substances, damages to persons due to explosions, fires and release of toxic substances, have also to be taken into account. Therefore, the usual safety requirements applied to civil buildings for ultimate and serviceability limit states, together with the consequences of exceptional actions, are generally unsuitable for structures belonging to industrial plants. As a matter of fact, a critical damage for a process safety that can cause even a modest release of inflammable substances, such as a flange opening or a welding breaking, can result unessential under structural point of view, but, at the same time, might cause considerable accidental chains. Consequently, for process industry it is necessary to associate the indirect consequences caused by possible accidents (i.e. a seismic event) to the direct structural damages.

During the last years, in order to increase safety against earthquakes, passive control techniques (PCT) have been developed, which are based on the concept of reducing the seismic action instead of increasing the strength (Housner et al., 1997). These techniques that for civil constructions are nowadays considered a consolidated alternative design tool, can also be used for seismic protection of industrial structures.

Unfortunately a very limited number of applications to industrial plants components have been realized. For this reason, in the present chapter the applicability of such a technique is investigated, aiming at providing general applicability criteria. An example of base isolation of a steel storage tank is also presented, whose effectiveness is investigated by a wide numerical and experimental activity.

## 2. Structural classification and seismic behavior of oil refinery components

A schematic representation of a refinery is shown in Figure 1(Moulein & Makkee, 1987). The raw material arrives in the refinery by different ways (by train, ship, pipelines, etc..), depending on the location, and then it is stored in big tanks.

The main operation in a refinery is the distillation of raw material in columns, named “topping”, that divide the crude oil in a certain number of fractions (5-7) distinguished in 1) light fraction (gasoline and light components), 2) intermediated fraction (Kerosene and light oils) and 3) heavy fraction (residual oils). All these fractions are processed further in other refining units to obtain specific products. For example the heavy fraction is subjected to a specific “thermal cracking” or “Visbreaking” treatment to obtain a certain quantity of more refined material.

The equipment deputed to these operations are indicated in Figure 2. In particular; (A) tanks for the storage of raw and refined materials, (B) process equipment for the chemical treatment of crude oil and waste material, (C) piping systems for the transferring of the material and (D) flares, used to eliminate waste gas. For a detailed description of the operation of each component that is beyond the aim of this chapter, the reader can refer to specialized publications (Mayers, 2004).

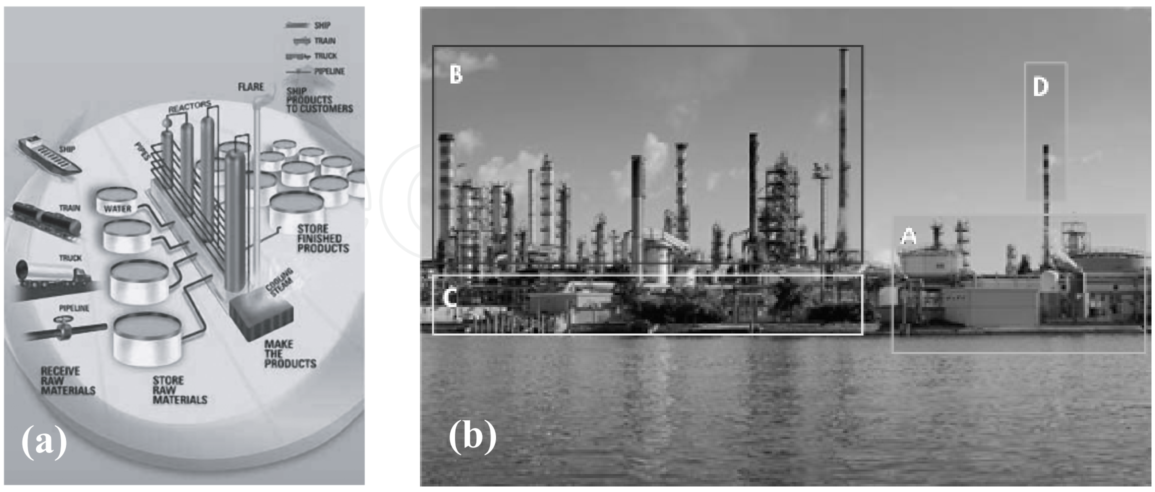


Fig. 2. (a) Schematic representation of an oil refinery, (b) Main components of a refinery.

During a transformation processes many dangerous substances are treated. Consequently, a refinery is equipped with numerous safety systems, some of which imposed by the codes and other adopted by designers. It is worth to highlight that during a seismic event they could fail, becoming useless. Therefore the seismic protection of a refinery must be mainly based on the reduction of the seismic risk of single components.

| Earthquake | Data | M |
|---|---|---|
| Kern Kounty (California, USA) | 21 July 1952 | 7.5 |
| Anchorage (Alaska) | 27 March 1964 | 8.6 |
| Nigata (Japan) | 16 June 1964 | 7.6 |
| Valparaiso (Chile) | 3 March 1985 | 7.8 |
| San Fernando (California, USA) | 9 Febbruary 1971 | 6.5 |
| Loma Prieta (California, USA) | 17 October 1989 | 6.9 |
| Costa Rica | 22 April 1991 | 7.6 |
| Kocaeli (Izmit, Turkey) | 17 August 1999 | 7.6 |
| Bhuj (Gujarat, India) | 26 January 2001 | 7.7 |
| Tokachi-Oki (Japan) | 26 September 2003 | 8.3 |
| Honshu (Japan) | 11 March 2011 | 9.0 |

Table 1. Important industrial plants struck by destructive earthquakes.

The experience derived from observing damages caused to industrial plants by past earthquakes can be very useful to identify the most exposed components to the seismic risk and the evaluation of the consequences. Despite the difficulties of obtaining and organizing data, detailed information on the behavior of the refineries in a certain number of earthquakes are available, in particular those listed in Table 1 (Kawasumi, 1968; Nilsen &

Kiremidijian, 1986; Scholl & Thiel, 1986; ATC-25, 1991; Showalter and Myers 1992; Beavers et al., 1993; Erdik & Durukal, 2000; Steinberg et al., 2000; Johnson et al., 2000; Suzuki, 2002; Kilic & Soren, 2003; Sezen & Whittaker, 2004; Hatayama 2008; Suzuki, 2006)

Based on this information, in the following, the main apparatus of process industrial plants are grouped into a restricted number of structural classes and the main observed damages caused by earthquakes are analyzed in detail.

### 2.1 Slim vessels

Cylindrical vessels with a high ratio height/diameter (between 5 and 30, and even higher) belong to this category. Among them, on the basis of the operation and the system of constraints to which they are subjected, it is possible to identify:

- Vertical cylindrical vessels which are directly anchored to foundations and free along the height. This category includes the distillation columns and many other reactors. The distribution of the mass along the height is usually rather uniform and it may be considered as continuous, even though some internal discontinuities could be present.
- Vertical cylindrical vessels which present additional constraints, besides at their basis, also along the height. This group includes very thin columns such as stacks and flares. Their mass is entirely due to the structure, because they contain just atmospheric pressure gas.
- Horizontal cylindrical vessels, supported by two or more saddles connected to a foundation platform. In this category many pressurized storage tanks and shell-and-tube heat exchangers are included.

As far as vertical slim vessels are concerned, the most common damages in case of seismic event are the failure at the foundation, due to the excessive stress, and the loss of contained fluids because of failure of connected flanges, due to excessive relative displacements. For example, during the *Loma Prieta* earthquake a refinery was seriously damaged, where the most important effect was on the anchor bolts of about 20 vertical vessels, on a total of 50 vessels. During the *Valparaiso* earthquake in a ventilation-stack with diameter 18” the anchor bolts were subjected to a similar damage, with the yielding of bolts.

The Izmit earthquake induced serious damages in the Tupras refinery. An entire unit was destroyed by the collapse of a chimney of a furnace 105 m high (Figure 3a). The top of the chimney collapsed on the furnace, whereas the bottom part collapsed on a pipe system. Even if the furnace was designed according to ACI-307, it has been subjected to an important damage.

### 2.2 Above-ground squat equipment

These apparatus have similar dimensions in the principal directions and are characterized by heavy masses; they can be grouped in two main categories:

- Large cylindrical steel storage tanks with a height/diameter ratio between 0.2 and 2. The roof can be welded to the shell (fixed conic roof) or floating over the contained liquid. The operating volume varies from some tens to 200000 $m^3$. The bottom plate is circular and placed directly on a granular backfill. When they are full filled, part of the mass oscillates under the seismic excitation producing high forces on the tank wall, whereas the remaining part induce a sloshing wave that might produce overtopping phenomena.

- Large process equipment like filters and decanters, or dynamic apparatus like pumps and compressors. They have large masses and are placed directly on high inertial foundations because of the dynamic action produced during the operating conditions.

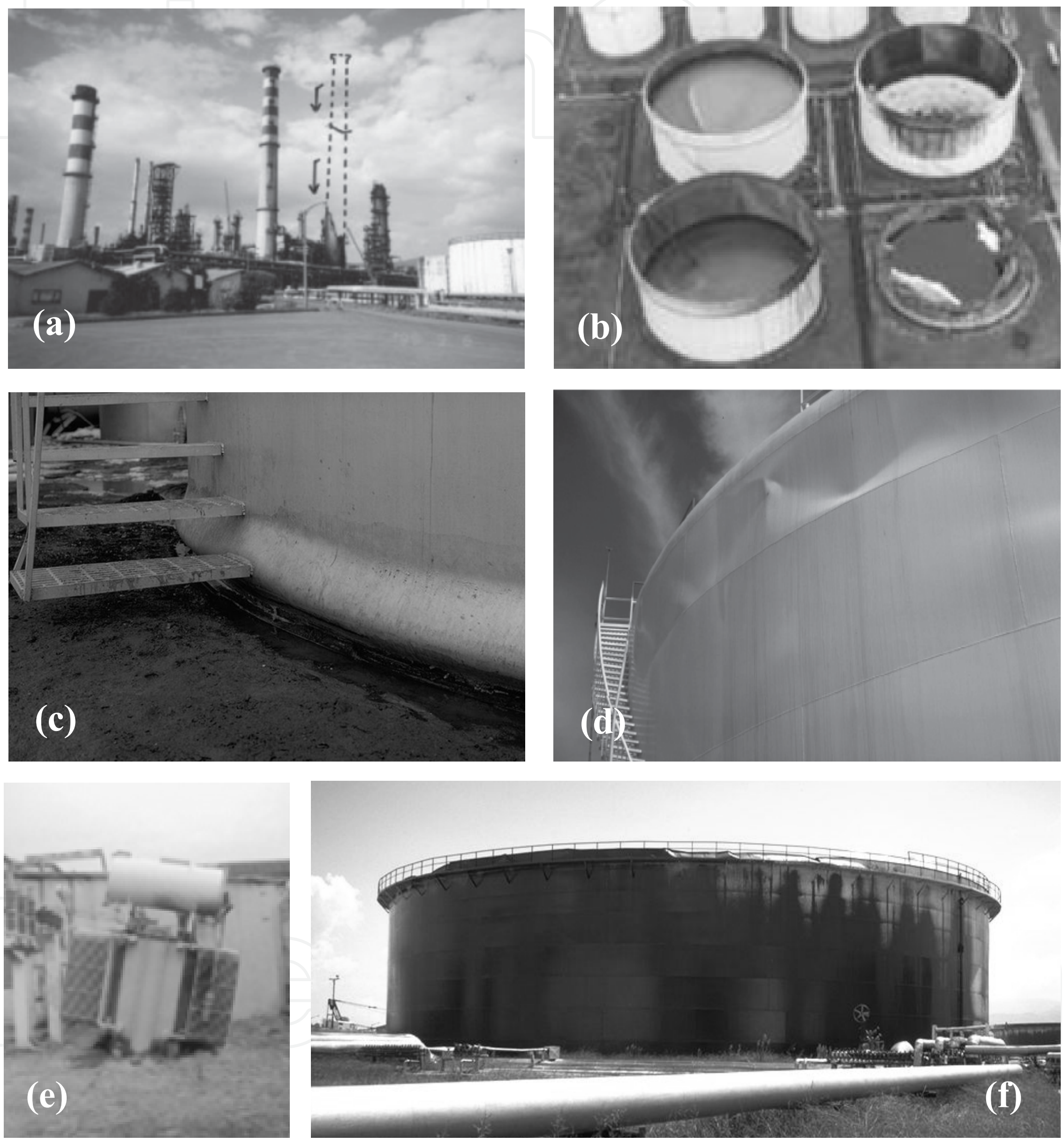


Fig. 3. (a) Collapse of a chimney at Tupras Refinery, (Itzmit, 1999), (b) Damages to tanks with floating roof (Tokachi-oki, 2003), (c) Elephant foot buckling (Anchorage, Alaska, 1964), (d) Elastic diamond buckling (San Fernando, California, 1971), (e) Collapse of an electric transformer, (f) Overtopping phenomenon in a big tank (Itzmit, 1999).

The typical damages associated to the first category are related to buckling phenomena of the wall (elephant foot buckling, sloshing buckling) or to failure of the wall-bottom plate joint. In Figure 3c and 3d examples of elephant buckling and elastic buckling are shown, respectively. But other possible damages are also possible, especially due to excessive sloshing motion, even in presence of floating roof, which can cause liquid overtopping and fire due to the crash between roof and wall. As a matter of fact, during the Itzmit and Tokachi-oki earthquakes, most of the tanks were destroyed for excessive sloshing motion (Figure 3b and 3f). Moreover, damages due to the uplift phenomenon of above ground tanks or ground settlements have been also observed during several seismic events, which have been capable to produce serious localized damage between wall and bottom plate.

### 2.3 Squat equipment supported by columns

In this category it can be included:

- Spherical storage vessels, essentially used for pressure liquefied gases. They are generally elevated with respect to ground by using steel columns placed along the circumference and welded to the shell at the equatorial level and normally linked each-other by diagonal braces (see Figure 4c).
- Vertical large storage vessels for cryogenic liquefied gas (LNG); their configuration is similar to that of the large atmospheric storage vessels for liquids, but their walls are realized by a double shell, in the inner-space of which an efficient thermal insulation is located; their bottom is anchored to a concrete plate, supported by short reinforced concrete columns (Figure 4a).
- Process furnaces and steam boilers. These equipments have the function to heat or vaporize large amounts of liquid products, according to the chemical process demand. Generally process furnaces are large structures, with few standardized shapes, mainly of cathedral type and vertical cylinder (Figure 4b). These furnaces are kept elevated from the ground by means of short reinforced concrete columns, according to the location of burners that requires pipes and space for maintenance. For these apparatus, the collapse is mainly due to the soft-story phenomenon caused by the shear failure of the short columns. The collapse of chimneys is also possible, as well as the detachment of pipes and of the internal wayward covering.

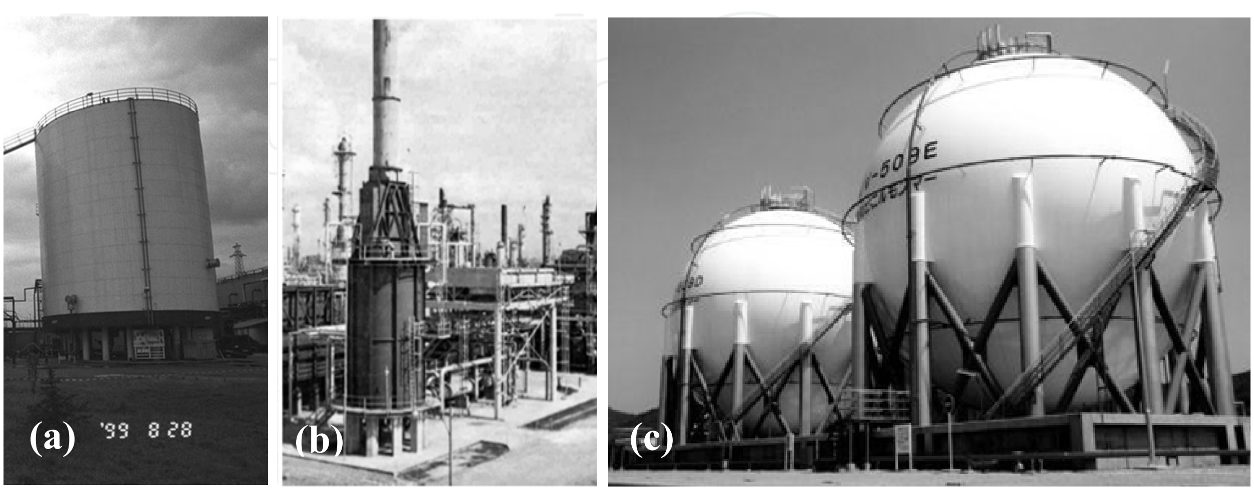


Fig. 4. (a) Damaged liquid oxygen and nitrogen tanks (Habas plant, Itzmit, 1999), (b) Cylindrical shape Furnaces (c) Spherical storage vessels.

During the Kern Kounty earthquake (California, 1952), at the Paloma Cycling Plant, two of the five spheres of butane collapsed, causing the cut of all the connecting pipes and creating a massive release of the content. The cloud formed quickly found a source of ignition in electrical transformers places a few hundred meters away. The result was a violent VCE (Vapor Cloud Explosion) followed by a fire of considerable proportions, see Figure 5a.

During the Itzmit earthquake some LNG tanks sustained by reinforced concrete columns were subject to important damages followed by the collapse of the basement, due to the insufficient shear strength of the columns (Figure 5b) (Sezen et al., 2007)

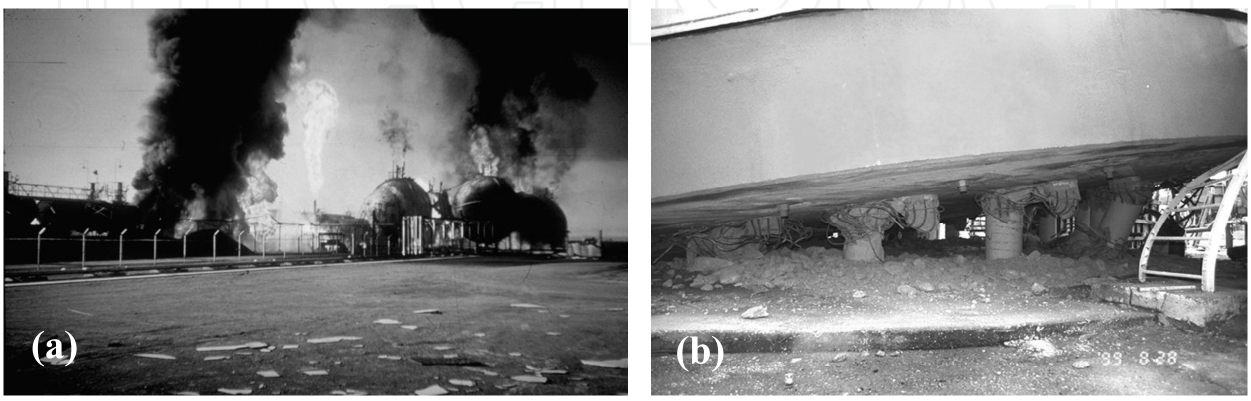


Fig. 5. (a) Butane sphere fire (K. Kounty, 1952), (b) Collapse of LNG tanks (Itzmit, 1999).

### 2.4 Piping systems

Piping systems connect all equipment involved in the process, transferring fluids within the plant (Figure 6a); as mentioned before, in a large refinery, hundreds kilometers of pipes of different size are installed; they are mainly realized with steel, but in some cases also with ceramics, glass, concrete, etc., if a specific performance against corrosion is required.

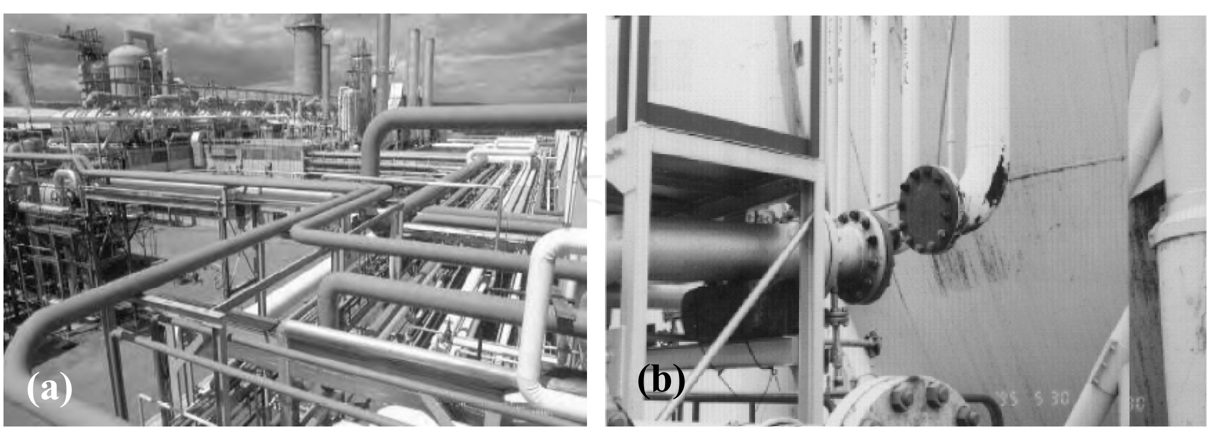


Fig. 6. (a) A piping system in a refinery, (b) Breakage of a piping flanged connection.

Metallic pipes themselves are not particularly vulnerable to seismic actions, but they can suffer the effects of differential displacements, which could not be compatible with the pipe deformations. Moreover, a collapse of the support structure can cause a catastrophic collapse of pipes, as shown in Figure 6b where the breakage of a piping flanged connection is shown.

### 2.5 Support structures

Piping systems, heaters, pumps, fans and other equipment, require a support structure. The geometrical configuration depends on different factors; consequently, they present different structures with irregular distribution of stiffness and strength. In addition, the structure is often modified according to the production requirements that can be necessary during the life-cycle of the plant. The support structures are mainly realized with steel frames, often stiffened by diagonal bracings. Nevertheless, structures realized with a different material are not rare, especially reinforced concrete and steel-concrete composite structures.

In the several reports dedicated to seismic effects in industrial plants, description of damages suffered by support structures are rare. During the Loma Prieta earthquake service frames of a reactor were subjected to limited damages. On the contrary, the support frame of a group of fans was subjected to severe damage as shown in Figure 7a. The structure was initially designed to support a piping system, but later was used for supporting the fans. Consequently, during the seismic event some of the beams collapsed for elastic instability.

Finally, collapse of the entire supporting structure due to the failure of the surrounding structures cannot be excluded. For example during the Itzmit earthquake in 1999 the chimney of Fig. 3a fallen down on a piping system causing important damages (Figure 7b)

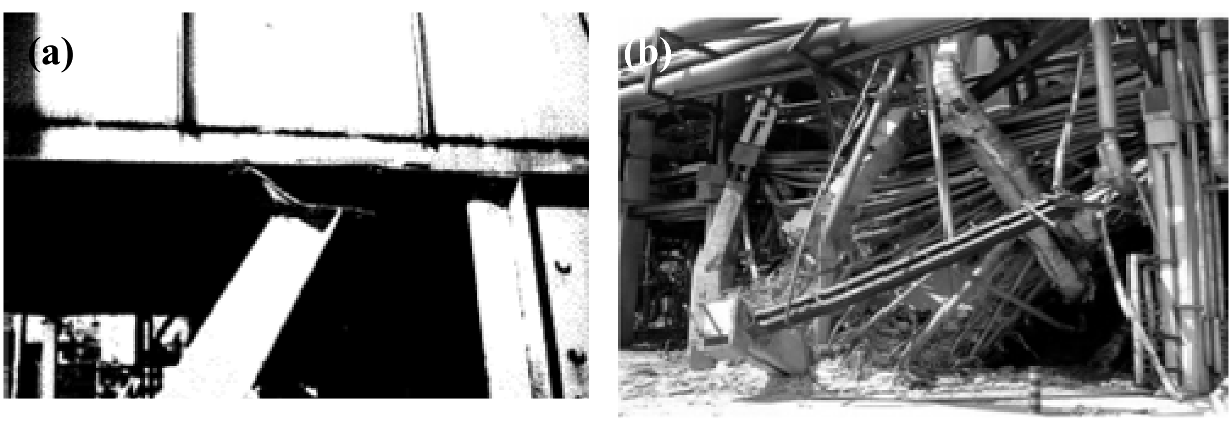


Fig. 7. (a) Damage to the supporting structure of fans (Loma Prieta, 1989), (b) Collapse of a piping system (Itzmit, 1999).

## 3. Applicability of passive control systems for the seismic protection of oil refinery components

### 3.1 Passive control techniques (PCT) for the seismic protection of industrial components

Innovative seismic control systems belongs to the world of the vibration control techniques of structures, which includes passive, semi-active, active and hybrid systems (Housner et al., 1997; Spencer, 2003; Christopoulos and Filiatrault, 2007). The experiences acquired during experimental activities and worldwide applications have indicated the passive control techniques as the most suitable solutions for the seismic protection of structures. These systems modify the stiffness and/or the dissipative properties of the structure, favoring the reduction of the dynamic response to seismic actions. They can be classified on the basis of the physical phenomenon adopted, and specifically: a) Seismic isolation, b) Energy dissipation, c) Tuned mass damper (TMD).

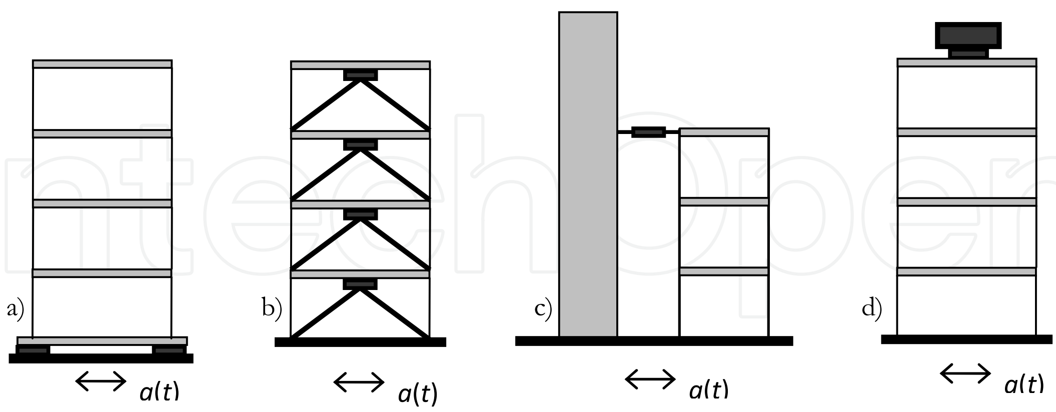


Fig. 8. PCS : a) base isolation, b) dissipative bracings, c) dissipative coupling, d) Tuned mass.

Base isolation systems produce a certain level of uncoupling between structure and ground. At this end, devices named “isolators” are usually placed at the foundation. Consequently, the structure is divided in two distinct parts: substructure and superstructure (Figure 8a); these devices are characterized by a high deformability in the horizontal direction and, at the same time, they are capable to transmit the vertical forces without appreciable deformations.

Isolators modify the dynamic characteristics of the structure, obtaining a high reduction of inertia forces. Unfortunately, there is a price to be paid: an appreciable increasing of displacements between substructure and superstructure. This inconvenient can be limited by increasing the energy dissipation capability of the structure using external dissipation devices or by a specific dissipative mechanism included in the isolators.

The isolation systems are usually subdivided in two categories: a) conventional devices, characterized by an elastic behavior, which realizes the elongation of the fundamental period of the structure, b) dissipative isolators, which in addition to the period elongation effect, increase the dissipation capability of the devices.

Dissipation control systems realize an artificial increasing of the structural damping with a consequent reduction of structural forces and displacements. Energy dissipation devices can be placed within the same structure through dissipative bracings (Figure 8b (Ciampi et al, 1995; Renzi et al., 2007), or between adjacent structures (dissipative coupling, Figure 8c) with different dynamic characteristics (Basili et al., 2007a, 2007b; Fraraccio et al., 2006).

Finally, using mass damping systems, namely TMD (Tuned Mass Dampers), the control of the seismic vibrations is carried out by adding auxiliary masses connected to the structure (conventional TMD). The additional damping is due to the transfer of energy form the structure to the auxiliary mass; this energy is then dissipated through dissipative devices placed between the structure and the auxiliary mass (Hoang et al., 2008). A non conventional TMD can also be defined: masses already present on the structure are converted into tuned masses, retaining structural or architectural functions beyond the mere control function (De Angelis et al, 2001).

The above techniques cannot be indifferently applied to each type of equipment of a plant, because their effectiveness depends on the characteristics of the structure to be protected. As a matter of fact, for a cathedral-type furnace (Figure 9a) the seismic isolation can be profitably used by inserting isolators between the superstructure and the base columns.

A typical situation to which the techniques of Figure b, c and d can be easily applied is shown in Figure 9b. In fact, dissipative bracings can highly reduce the seismic response of the steel frame. Alternatively, the equipment placed at the several floors of the frame can be used as TMDs connecting them to the frame using dampers. Moreover, being distillation column and frame adjacent structures, they can be coupled using dissipative devices (Paolacci et al., 2009; Paolacci et al., 2010)

Until now, passive control techniques have been used for a very limited number of industrial applications; for example, in Europe the isolation technique has been adopted only in a few cases: the seismic protection of Petrochemical LNG terminal of Revythousa, Greece (Tajirian, 1998) and of ammoniac tanks, at Visp, in Switzerland by means of elastomeric isolators (Marioni, 1998), Figure 20. Friction Pendulm devices have also been used for the seismic isolation of an elevated steel storage tank of the petrochemical plant of Priolo Gargallo in Sicily (Italy) (Santangelo et al., 2007).

It is worth to observe that damages like leakage of a flanged joint or breakage of a welding, usually considered critical for the safety of the transformation process, are instead treated as unessential under structural point of view, even if might generate important accidental chains. Therefore, for the process industry, unlike civil structures, it is necessary to associate the direct damage inflicted by the earthquake, with the indirect consequences of possible incidental chains.

The experience provided by the observation of seismic damages suffered by industrial plants allows recognizing the most vulnerable components. Assuming that one of these components is damaged and considering this as an initiator event, using a classic analysis of "event tree", the risk of the various consequences could be assessed.

The first step is then to identify the most likely initiator events of accidental chains that can lead to serious consequences. Table 2 summarizes the typical observed damage and accidents due to earthquakes of some major industrial equipment together with the suggested passive techniques for their seismic protection. For slim vessels, the most likely damage in case of earthquake is the yielding of anchorage bars at the foundation level and the leakage of fluid due to failure of flanged joints caused by excessive displacements. In this case, the most appropriate passive control technique seems to be the dissipative coupling between vessel and adjacent structures (Ciampi et al., 2006). As far as above ground broad tanks is concerned, typical observed damages (failure of wall-bottom plate welding, elephant foot buckling, elastic buckling of wall, settlements of the ground under the tank) can be eliminated using base isolation technique (De Angelis et al., 2010). Other accidents and possible damages due to sloshing motion in presence of floating roof (overtopping, fire due to impact between the roof and mantle), are neither amplified nor reduced by the isolation. A possible solution to reduce the effects of the impact between floating roof and tank wall can be represented by spacers placed between roof and wall or by inserting a TMD system into the roof (for eg. a Tuned Mass Damper Column, (Sakai and Inoue, 2008).

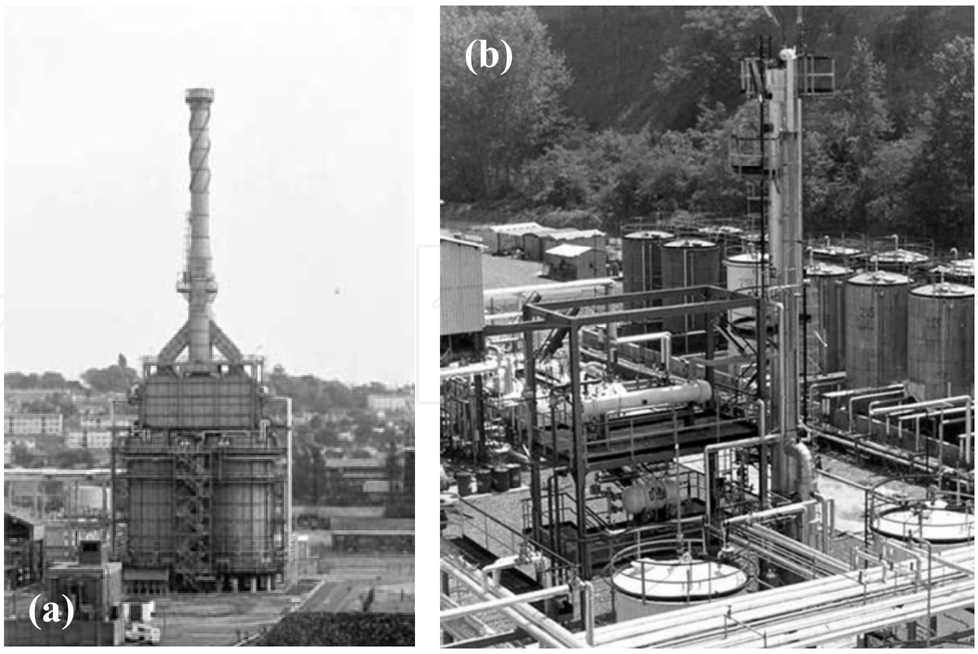


Fig. 9. a) Cathedral furnace where the seismic isolation can be easily applied, b) Distillation column and adjacent steel frame in which is possible to realize: dissipative bracings in the steel frame, dissipative coupling between column and frame, and Tuned Mass Damper, linking the equipment placed at several levels of the frame with the same frame using proper isolators.


Fig. 10. a) Base isolation of a LNG tank at Revythousa Island (Grecee), b) Base isolation of an elevated tank ammoniac tanks at Visp, Switzerland, c) Dissipative bracings solution for elevated tanks, d) dissipative coupling solution for elevated tanks.

For squat equipment placed on short columns the base isolation technique appears to be highly effective. The unique drawback is represented by the increasing of relative displacement between the apparatus and the surrounding ones. For this reason proper counter-measures have to be adopted to preserve the integrity of the connected pipes, for example flexible joints.

The use of dissipative bracings can be effective (Figure 10c) (Drosos et al., 2005). These devices reduce stresses and displacements, but can be invasive and limit the operation of the equipment. In some cases, like spherical tanks, the dissipative coupling can also be used in conjunction with auxiliary reaction structures (Figure 10d) (Addessi et al., 2001).

For process furnaces, beyond the base isolation technique, a sophisticated solution may consist in designing the chimney as a TMD system, adding an auxiliary mass at the top (Balendra et al., 1995).

| Structural typology | Critical equipment | Typical seismic observed damages | Other possible dameges | Passive control techniques |
|---|---|---|---|---|
| Slim vessels | Columns<br>Reactors<br>Chimney<br>Torch | • Leakage of fluid in flanged joints<br>• Yielding of anchor bars | Overturning | Dissipative coupling |
| Above-ground squat equipment | Big broad tanks with fixed and floating roof | Failure of wall-bottom plate welding<br>Elephant foot buckling | Uplifting | Base isolation |
| | | Diamond buckling of tank wall<br>Settlements of ground<br>Impact of floating roof to tank wall. | Overtopping<br>Torch fire | dissipative spacers between roof and wall, TMD |
| Squat equipment placed on short columns | Spherical tanks | Collapse of structure due to shear failure of columns | | Dissipative bracings<br>Base isolation<br>Dissipative coupling |
| | Process Furnaces | Collapse of structure due to shear failure of columns<br>Collapse of the chimney<br>Detachment of internal pipes<br>Detachment of the internal refractory material | Leakage from pipes;<br>Increase of temperature of Furnace wall | Base isolation<br>Dissipative bracings<br>TMD |
| | Cryogenic tanks | Collapse of structure due to shear failure of columns | | Base isolation |
| Piping systems and support structure | Steel or R.C. frames | Collapse for excessive stresses | Damages to supported equippment (pipes, tanks,..) | Dissipative bracings<br>Dissipative coupling<br>TMD (using the same supported equipment) |

Table 2. Seismic damages of industrial process components and passive control systems.

Finally 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, as for the slim vessels. To avoid damage in the supported equipment (compressors, pumps, tanks, etc..), the TMD technique can also be adopted. In this case, it is possible to reduce the stress level in the frame and contemporarily to protect the equipment used as TMD. In this case, special dampers like wire-ropes could be profitably used (Paolacci and Giannini 2008).

The innovative technologies for the vibration control are also effective to preserve integrity and operational continuity of equipment.

An effective way to protect seismic vulnerable equipment consists in implementing an isolation system between the internal apparatus and the supporting structure. There are two configurations proposed in literature: the apparatus to be isolated may correspond either to an individual raised floor (Hamidi and El Naggar, 2007), on which a group of several equipment is anchored (isolated raised-floor systems or floor isolation systems, (Alhan and Gavin, 2005), or to a single equipment itself (equipment isolation systems), especially when having a large mass (De Angelis et al., 2011). As a result, the absolute accelerations transmitted to equipment are considerably reduced and the damages due to excessive inertial forces are prevented.

Passive linear and nonlinear isolation systems have been proved to be effective and practical to protect acceleration sensitive equipment from earthquake hazard [Reggio and De Angelis, 2011].

## 4. Example: Application of two isolation systems for the seismic protection of above-ground steel storage tanks

### 4.1 Introduction

In this section, the effectiveness of the base isolation on steel storage tanks is investigated through numerical models and then checked by shaking table tests on a reduced scale (1:14) physical model of a real steel tank (diameter 55m, height 15.6 m), typically used in petrochemical plants. In the experimental campaign the floating roof has also been taken into account.

In practice, in order to evaluate the effect of the sloshing, many seismic design codes adopt the formula relative to free surface conditions, (European Committee for Standardization, 2003; American Petroleum Institute 2007). This is justified by theoretical studies (Sakai and Nashimura, 1984), where is shown that the effect of the floating roof has a negligible influence on the frequency and amplitude of the first vibration mode and it is confirmed by the experimental study presented in the following.

The tests have been carried out using the six d.o.f. 4 x 4 m shaking table installed in the laboratory of ENEA (Italian National Agency for New Technologies, Energy and the Environment) Research Centre "La Casaccia" at Rome, Italy. The tests have been performed on the physical model both in fixed and isolated base configurations; in particular two alternative base isolation systems have been used: high damping rubber bearings devices (HDRB) and PTFE-steel sliding isolation devices with c-shaped elasto-plastic dampers (SIEPD).

In the following, after a brief presentation of the dynamic behavior of tanks, with and without base isolation systems, the main results of the experimental tests are shown and discussed. Finally, a comparison between experimental and numerical results has been illustrated. A detailed description of the experimental campaign can be found in (De Angelis et al. 2010).

### 4.2 Dynamics of liquid storage tanks

#### 4.2.1 Fixed base tanks

The dynamics of cylindrical tanks subjected to a base motion has been extensively studied by several authors. Starting from the earliest work of Housner (1963), the hydrodynamic pressure induced by the liquid on the tank wall due to the base motion has been determined, taking into account the deformability of the tank wall; see for example (Fisher, 1979; Haroun & Housner, 1981; Velestos & Tang 1987).

In brief, the liquid mass can be imagined subdivided in two parts: an impulsive component, which follows the base motion and the deformability of the tank wall, and a convective component, whose oscillations cause superficial wave of different frequency with a very low percentage of mass (≈4%) relative to the higher modes; moreover, while in the slender tanks the most part of the liquid moves rigidly with the tank, in the broad tanks most of mass oscillates in the convective modes.

Under the hypothesis of rigid tank, the impulsive and convective part of hydrodynamic pressure can be easily evaluated. On the contrary, the part, which depends on the deformability of the tank wall, can be determined solving a fluid-structure interaction problem, whose solution depends on the geometrical and mechanical characteristics of the tank: radius $R$, liquid level $H$, thickness $s$, liquid density $\rho$ and elastic modulus of steel $E$. The problem can be uncoupled in infinite vibration modes, but only few of them have a significant mass. Thus, the impulsive mass is distributed among the first vibration modes of the wall.

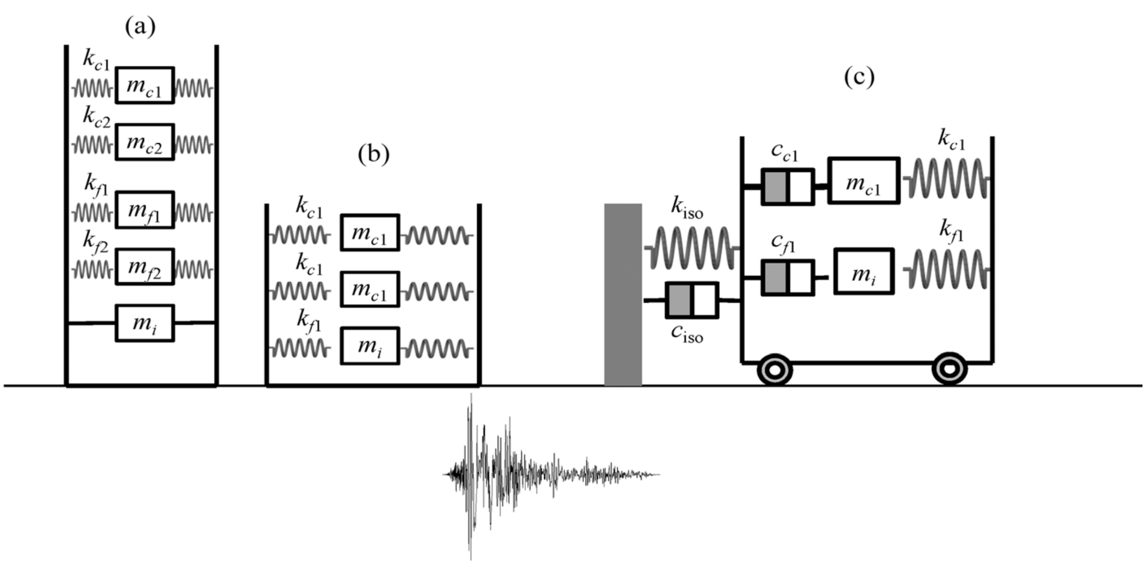


Fig. 11. (a) Equivalent spring-mass model: (a) general, (b) broad tanks (c) Dynamic model of a base isolated broad tank.

On the basis of the above observations it can be drawn that the study of the hydrodynamic pressure in tanks subjected to a seismic base motion can be easily performed using the simple model shown in Figure 11, in which the liquid mass is lumped and subdivided in three components: rigid, impulsive and convective masses named $m_i$ , $m_{ik}$ (mass of k-th mode of the wall vibrations), $m_{ck}$ (mass of k-th convective mode). The impulsive and convective masses are connected to the tank wall by springs of stiffness $k_{ik}$ and $k_{ck}$. The total pressure is given by adding the effects of the mass mi subjected to the base motion acceleration, of the masses $m_{ik}$ subjected to the acceleration of the wall relative to the bottom of the thank, and of the masses $m_{ck}$ subjected to the absolute acceleration.

In case of broad tanks the model of Figure 11(a) can be updated by the simplest model shown in Figure 11(b). In fact, the contribution of the higher order vibration modes is negligible and the entire impulsive mass is practically equal to the mass of the first vibration mode; moreover, because the distributions of the impulsive pressure, with and without wall deformability, are almost coincident, the effects of the impulsive action are simply taken into account by the response in terms of absolute acceleration of a simple oscillator of mass $m_i$ and stiffness $k_i$. Neglecting the higher convective modes effect, the model becomes a simple two degrees of freedom model. The frequencies of the convective and impulsive modes are generally very different (tenths of a second against tens of seconds). This justifies the usual choice of neglecting the interaction between these two phenomena.

### 4.2.2 Base isolated tanks

As shown in section 2, the idea of seismic protection of tanks through base isolation technique is not really new, but the important amount of numerical investigation present in literature has proved its high effectiveness. Unfortunately, a limited number of experimental activity has been performed so far (Bergamo et al., 2007; Summers et al., 2004; Calugaru and Mahin, 2009).

On the basis of the observations of the previous section a dynamic model of a base isolated tank can be easily built. For example a simple model of base isolated broad thanks is shown in Figure 11(c).

The vibration period of the impulsive component of pressure generally falls in the maximum amplification field of the response spectrum, whereas the convective period $T_c$ is usually very high and thus associated with a low amplification factor. This implies a high effectiveness of the base isolation system, which can reduce highly the base shear due to the impulsive pressure component. Neglecting the influence of the wall deformation, the period of the isolated structure is approximately given by:

$$T_{iso} \approx 2\pi\sqrt{\frac{m_i + M_s + M_b}{k_{iso}}} \tag{1}$$

in which $m_i$ is the impulsive part of the liquid mass, $M_s$ and $M_b$ are respectively the wall and base tank masses, and $k_{iso}$ is the elastic stiffness of the isolators.

For broad tanks $m_i$ is a relatively small part of the total mass and this allows a significant reduction of the devices dimensions.

Moreover, in the case of big tanks, for which $T_c >> T_{iso}$, the first period of the convective motion is practically unmodified. Consequently, the base isolation system does not show any important mitigation effects on the sloshing pressures. This is not relevant, since the convective pressure is very small because of the long period of the fluid oscillations.

The negative effect of the sloshing is related only to the superficial motion, because either the height of the wave can exceed the upper limit, causing overtopping phenomenon, or the floating roof motion could cause a breaking of the gaskets and the leakage of dangerous vapours of inflammable substances. Unfortunately, the base isolation does not modify this phenomenon. Moreover, the base isolation can cause high displacements between tank and ground, which may induce dangerous damage to the pipes-tank connections.

### 4.3 Shaking table tests

#### 4.3.1 Description of the physical model

The full scale structure is a big steel liquid storage tank typically installed in petrochemical plants. The dimensional characteristics of the tank are the following: radius R=27.5m, height Hs=15.60 m, liquid level H=13.7 m, liquid density ρ=900 kg/m3, and wall thickness variable from 17 to 33 mm. The scale model has radius R=2 m, height Hs=1.45 m and wall thickness s=1 mm (Figure 12a). Thus, the scale ratio is about 13.7.

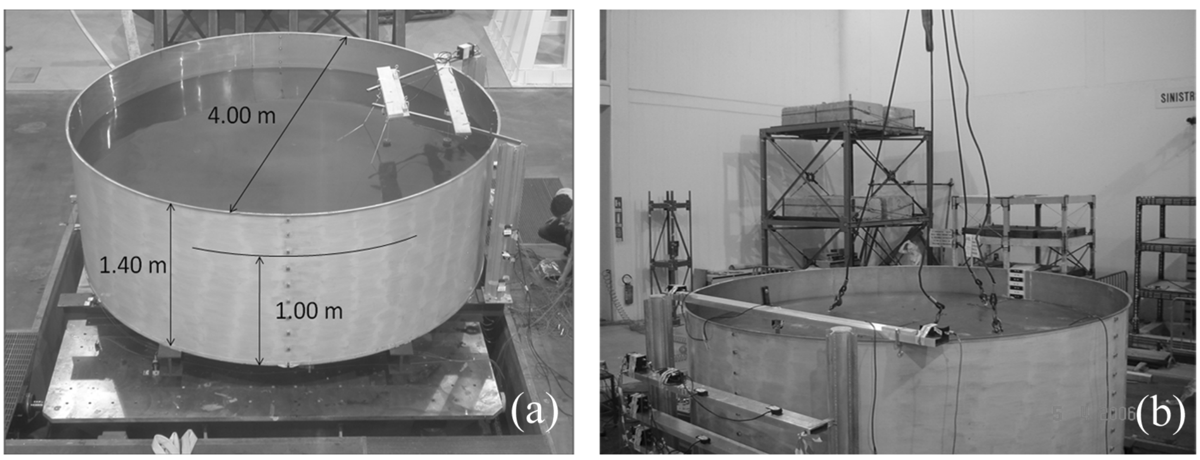


Fig. 12. (a) Tank without floating-roof, (b) Floating roof installed on the mock-up.

Because the period of the sloshing mode is a function of the square root of the dimensions (European Committee for Standardization, 2003), the time scale of the convective motion is 3.7. In order to obtain the same scale ratio for the impulsive frequencies it would be necessary to reduce the thickness of 140 times with respect to the real one. This is obviously impossible and only one time scale can be respected. In particular, the convective motion scale has been adopted during the test (De Angelis et al., 2010).

The floating roof of the full scale tank is realized through a truss structure, which sustains steel plates. In order to maintain the mass ratio, the floating roof of the mock-up has been realized with a wood structure (Figure 12b). The gasket, which in the full scale tank is composed by a more complex mechanism, has been here realized with a rubber tube applied along the circumference of the roof.

#### 4.3.2 Design of base isolation systems

For the seismic protection of the tank two isolation systems has been used: high damping rubber bearings (HDRB) and PTFE-steel isolation devices with metallic c-shaped dampers

(MD). Both the base isolation systems have been designed by choosing a properly isolation period ($T_{iso}$) and then evaluating the stiffness $k_{iso}$ using the equation (1). For the high damping rubber bearings the damping ratio $\xi$ has been assumed equal to 10% whereas the yielding force of the metallic dampers has been designed using the method proposed by (Ciampi et al., 2003).

The prototypes of the isolator devices, properly realized for the experimental activity by the Company Alga Spa (Milan), are shown in Figure 13a and 13b. The isolators have been characterized by cyclic imposed displacement tests carried out in the experimental laboratory of the University of Roma Tre. The main characteristics of the devices are summarized in Table 3.

In order to check the effectiveness of the control systems, for each isolator typology four devices have been used, which have been placed at the cross of the bottom metallic beams.

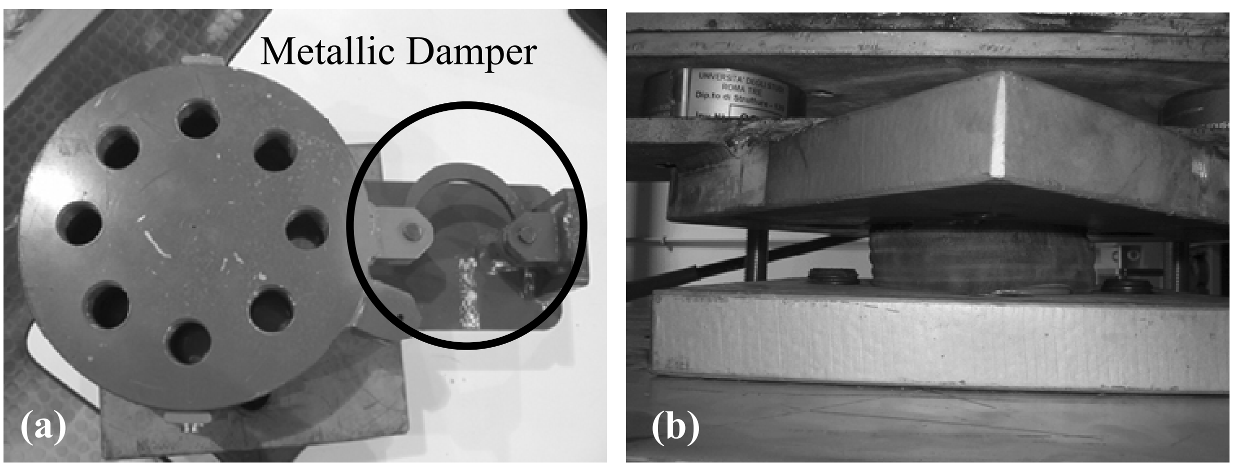


Fig. 13. (a) Sliding bearing with dissipative damper, (b) High Damping Rubber Bearing.

| | HDRB | MD |
|---|---|---|
| Isolation period in real scale (sec) | 2.8 | 1.6 |
| Initial stiffness(kN/m) | 900 | 1617 |
| Yielding strength (kN) | 3.00 | 7.880 |
| hardening ratio | 0.40 | 0.05 |
| Fiction coefficient | -- | 2-3% |

Table 3. Isolation devices characteristics.

#### 4.3.3 Test set-up

A series of dynamic tests have been carried out on the tank using the shaking table installed at the Research Center of ENEA "La Casaccia" (Rome). The mock-up has been tested in four different configurations: fixed base tank without floating roof (case A), fixed base tank with floating roof (case B), isolated tank with HDRB and floating roof (case C), isolated base tank with SIEPD devices and floating roof (case D).

Six different base motion histories have been used in each configuration (four natural and two synthetic accelerograms, generated by Simqke (Vanmarcke and Gasparini, 1976), according to the European code spectra (soil C), and scaled to different intensity levels). For all accelerograms the time scale has been changed according to the indications of section 3.1. The natural accelerograms have been selected from the Pacific Earthquake Engineering Research center database, between time histories recorded for soil C and generated by seismic events with magnitude lower than 8 and epicenter distance lower than 50 km. Another more selective criterion, adopted here, consists of a selection of signals filtered using a high-pass filter with cut-off frequency greater than 0.1 Hz. As already seen, this is almost the frequency of the sloshing motion of the full scale tank. The records used during the tests are reported in Table 4. The tank has been also tested using white-noise and harmonic signals with variable frequency (sine-sweep) for the identification of its dynamic characteristics.

The response signals were measured using numerous sensors: pressure transducers, strain-gauges and laser transducers placed on the tank wall. Laser transducers have also been used for the sloshing motion of the liquid or floating roof, whereas the motion of the table has been monitored by several accelerometers. In the isolated base configurations the motion of the structure with respect to the base has been measured by wire LVDT sensors. The arrangement of the sensors has changed between the several series of tests.

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| Accelerogram | M | Distance (km) | PGA (g) | Duration (s) |
|---|---|---|---|---|
| Irpinia, 11/23/80,Sturno, 270 | 6.5 | 32 | 0.313 | 40.00 |
| Duzce 11/12/99, Duzce, 180 | 7.2 | 8.2 | 0.482 | 25.88 |
| Kocaeli 08/17/99, Arcelik,090 | 7.4 | 17.0 | 0.149 | 28.00 |
| Chi-Chi 09/20/99, TCU120, w | 7.3 | 8.1 | 0.268 | 90 |

Table 4. Characteristics of the natural records used during the experimental test.

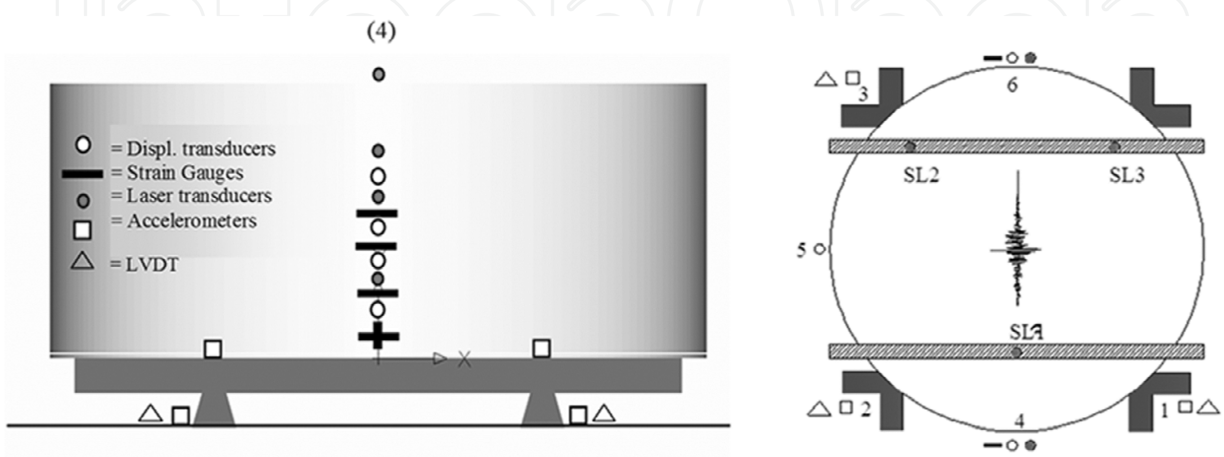



Fig. 14. Experimental Set- up.

### 4.3.4 Analysis of results

#### 4.3.4.1 Identification of dynamic characteristics

Before evaluating the seismic effects, the main dynamic characteristics of the tank (frequencies and damping) have been identified. The frequencies of the systems have been determined by means of the transfer functions between the input (base acceleration) and output signals (e.g. liquid pressure). The damping ratio has been evaluated using the logarithmic decrement method applied to free vibrations time histories. For each vibration mode, the signal has been filtered using a pass-band filter around its frequency.

In Figure 15 the transfer functions between the table acceleration and one of the pressure sensors (near the bottom of the tank) are shown for the fixed base configurations (A and B), without (Figure 15a) and with floating roof (Figure 15b). For both cases, the frequency of the sloshing motion does not change and is almost coincident with the theoretical value (0.4 Hz), whereas a resonant frequency of around 18 Hz is also shown, which correspond to the main natural frequency of the motion due to the deformability of the wall.

The damping of the sloshing motion has been measured on the basis of the amplitude decrement of free vibrations. In case of free liquid surface the damping is very low and is not in practice measurable; using the floating roof a 1% of damping has been identified. This value, greater than 0.5%, usually adopted in numerical model, is probably due to the interaction between the liquid surface and the floating roof and the friction between rubber gasket and tank wall-

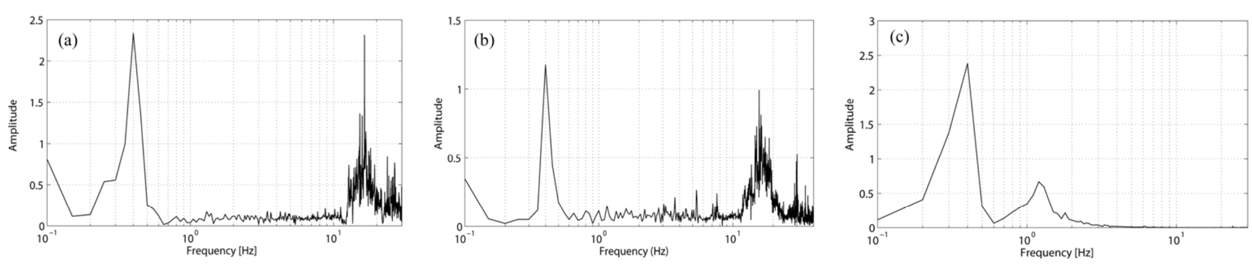



Fig. 15. Transfer functions: (a) pressure transducer, case A, White Noise, (b) pressure transducer, case B, White Noise, (c) LVDT, case C, ARC090.

The free vibrations of the floating roof for the isolated tank are shown in Figures 15c. The signals have been filtered in order to remove the frequencies greater than 1 Hz. Comparison with the results of non isolated case results, a considerable increasing of the sloshing damping, variable in the range 2.5-3.0%, for both isolated configurations has been detected. This increment was expected by numerical models, carried out with non-classical damping theory, but with lower values than the experimental ones.

#### 4.3.4.2 Response of the base isolated tank

The evaluation of seismic effects on the tank wall has been made in terms of both maximum base shear induced by the dynamic pressure and relative impulsive and convective components.

These resultants have been evaluated interpolating the experimental values of the pressure with the relative theoretical functions and then integrating along the height. The separation of the sloshing and impulsive plus flexible components was obtained by filtering the signals around the corresponding frequencies.

The responses of the table, measured in the different experimental tests, because of some problems with the control system, were different, even if the same accelerograms were used. Because of these differences, comparison was difficult. To overcome this problem the comparison was done in terms of mean spectra accelerations Sa, (5% of damping), calculated in the period range 0.05 and 0.1 s (10 ÷ 20 Hz) for the impulsive component, and 2.2-2.8 sec (~ 0.35 ÷ 0.45 Hz) for the sloshing component. Impulsive and sloshing forces have been represented as functions of the relative spectra acceleration (Figures 16a and 16b).

In the same figures the interpolation curves of the experimental data are shown for the fixed base (case B) and isolated base cases (case C, case D). For the fixed base case the trend is linear, whereas the isolated base cases clearly show a nonlinear behavior of the phenomenon, especially for high values of spectral acceleration.

The total shear has been plotted as function of the same spectra ordinate as that used for the impulsive component, the latter being a significant part of the total one (Figure 16c). The figure clearly shows the high effectiveness of both the isolation systems, which induce considerable reductions of the total shear affecting the tank wall. However, whereas the effectiveness of HDRB isolators does not practically vary with $S_a$, the effectiveness of SIEPD devices is reduced for low values of spectral acceleration, and it is practically negligible for Sa<0.3g.

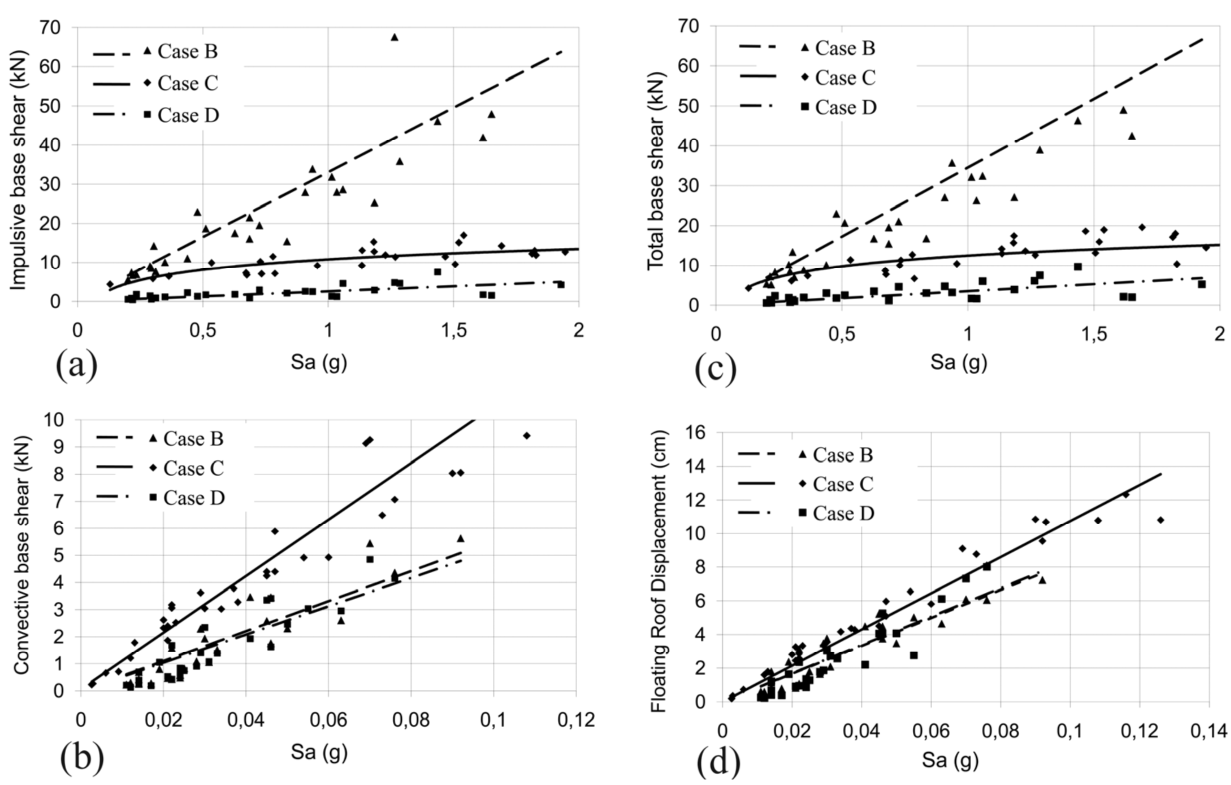



Fig. 16. (a) Impulsive base shear versus spectral acceleration of the impulsive motion, (b) convective base shear versus spectral acceleration of the convective motion, (c) total base shear versus spectral acceleration of the impulsive motion, (d) maximum displacements of the floating roof versus spectral acceleration of the convective motion.

This is due to the friction effects, often neglected for this kind of device, but particularly significant for the tanks, in which the gravity mass, represented by the entire liquid volume, is greater than the dynamic mass, which is represented by the impulsive mass only (in the present case only 30% of the total mass). Therefore, to overcome the friction appreciable levels of acceleration are needed. This problem is not present for elastomeric devices.

This behavior, if appropriately controlled, could represent an interesting advantage recognizable to SIEPD devices compared to HDRB devices. In fact, for low levels of seismic intensity, it could be convenient to use an isolation device with a reduced amount of slip, which instead is required for more intense events in order to achieve a full employment of the dissipation capability of the devices.

For the impulsive component (Figure 16a), the reduction is quite important, as already observed for the total base shear, especially for high values of Sa; on the contrary, the sloshing component (Figure 16b) remain practically unchanged for HDRB, whereas a slight increasing has been observed using SIEPD. This increasing has no influence on the stresses of the tank wall, at least for large broad tanks. The negative effects are related to the floating roof oscillations, which could generate, in some cases, the breaking of the gaskets and the leakage of inflammable materials. Unfortunately, the base isolation does not reduce the amplitude of the superficial waves, although the sensible increasing of damping reduces its duration and then probably the risk of failure of the gaskets. However, for case D only an increasing of the convective pressure has been measured, which has induced a rather moderate increasing of the amplitude displacement of the floating roof that does not seem to be not particularly worrying (Figure 16).

Finally, the maximum values of displacements of the tank base, recorded during the tests of case D and here not shown for brevity (De Angelis et al. 2010), are lower than the displacements of case C. This is another advantage for the SIEPD isolation system, since large displacements, which have to be absorbed by the pipes-tank connections, represent a problem, the solution of which is not always easy.

#### 4.3.4.3 Comparison between numerical and experimental results

The numerical model defined in section 3.2 has also been used to carry out step-by-step non linear analyses using as base motion the accelerograms recorder on the shaking table during the tests. The isolator devices have been modeled by the classical Bouc-Wen model. The aim is to confirm the reliability of the analytical and numerical formulation of the problem, also when the floating roof is present, generally missing in the evaluation of the dynamic response of tanks.

As a matter of fact, hereafter a numerical-experimental comparison of the results of cases B, C and D, is presented and discussed. For brevity only the results of the Arcelik accelerogram, scaled to the nominal acceleration nearest to the design value (0.5g) are shown.

Figure 17 shows the comparison, in terms of base shear for case B. Firstly, a good agreement between the experimental and numerical response may be noted. A good predictive capacity of the model emerges when the floating roof is present as well.

The numerical-experimental agreement can be better highlighted by analyzing the single components of motion. Figure 17a shows, for case B, the base shear due to impulsive pressure. The agreement is quite good and sufficient to correctly describe the phenomenon.

For the convective component of motion, although the value of the fundamental frequency was very close to the theoretical value (0.4 Hz), the comparison between numerical and experimental results proved unsatisfactory, because of non-zero initial conditions due to a low damping of the liquid motion. The numerical-experimental agreement is improved in the cases C and D. In fact, in these cases the fluid-structure interaction become less important and the high damping of the liquid motion arrests oscillations more rapidly, allowing zero initial conditions.

For the isolated tank Figures 17b and 17c show the comparison between theoretical and experimental results. The good agreement proves the reliability of the model.

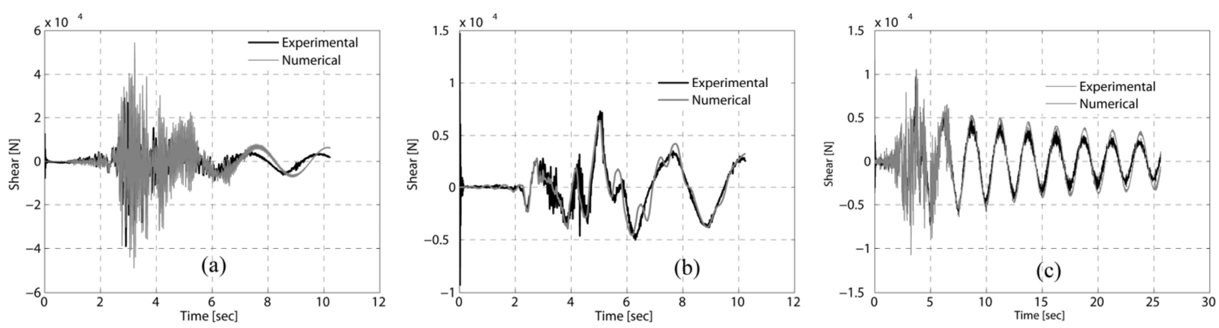



Fig. 17. Total base shear. Numerical-Experimental comparison, (a) case B, (b) case C, (c) case D, Arcelik 0.5g.

To summarize, the comparison between the shaking table test results and the response of simple numerical models described in section 2 shows the suitability of the latter to simulate the behavior of the fluid-structure system, both for fixed base and isolated base tank, also considering the floating roof as well. Actually, the slight discrepancies between numerical and physical models are probably due to some drawbacks in the experimental activity, caused by the high mass of the filled tank and the frequencies range investigated.

## 5. Conclusions

Recently, the attention paid on the protection of industrial facilities against natural phenomena is increasing, especially for the catastrophic consequences of strong events that induced severe damages to people and environment.

Among the natural phenomena capable to determine serious hazards to industrial plants, earthquakes should be taken into account especially because they are capable to generate multiple sources of releasing of dangerous substances and domino effects within the same plant, determining the complete destruction of the site. The analysis of past accidents induced by earthquakes has shown the high vulnerability of some typical industrial components and the severity of the consequences.

Accordingly, in this chapter, earthquakes effects on major-hazard industrial plants have been analyzed. In particular, typical equipment and components of a refinery were identified and gathered in a limited number of structural typologies; furthermore, their seismic vulnerability was analyzed, looking into historical events, i.e. concerning the damages caused by past earthquakes to several industrial components.

Subsequently, the applicability of some innovative techniques for the seismic protection of industrial equipment was studied and the most suitable passive control techniques were identified for each structural typology. As an example, the main results of a study on the effectiveness of yielding-based and HRDB isolators for the seismic protection of above-ground steel storage tanks were presented. In particular, after a brief introduction to the problem of designing a base isolation system for storage tanks, the outcome of a wide numerical and experimental investigation on a broad tank with floating roof were deeply discussed. Shaking table test results have shown the high efficiency of both the isolation systems and, at the same time, the reliability of lumped mass model for the prediction of the seismic response of isolated above-ground tanks.

## 6. References

Addessi D., Ciampi V. (2001), Ongoing studies for the application of innovative anti-seismic techniques to chemical plant components in Italy, 7th International Seminar on Seismic Isolation, Passive Energy Dissipation and Active Control of Vibrations of Structures, Assisi.

Alhan, C., Gavin, H.P. . Reliability of base isolation for the protection of critical equipment from earthquake hazards. Eng Struct 2005;27:1435–49.

ATC-25. (1991) Seismic vulnerability and impact of disruption of lifelines in the conterminous United States, (Applied Technology Council, Redwood City, CA).

API 650, (2007), Welded Tanks for Oil Storage, Edition: 11th Ed., American Petroleum Institute.

Balendra T, Wang C. M., Cheon N. F., (1995). Effectiveness of tuned liquid column dampers for vibration control of towers. Engineering Structures 17(9), 668-675.

Basili M; De Angelis M. (2007a). A reduced order model for optimal design of 2-MDOF adjacent structures connected by hysteretic dampers. Journal of Sound and Vibration, vol. 306; p. 297-317, ISSN: 0022-460X

Basili M; De Angelis M. (2007b). Optimal passive control of adjacent structures interconnected with non-linear hysteretic devices. Journal of Sound and Vibration, vol. 301; p. 106-125, ISSN: 0022-460X

Beavers, J.E., Hall, W.J. and Nyman, D.J. (1993) "Assessment of Earthquake Vulnerability of Critical Industrial Facilities in the Central and Eastern United States," In: Proceedings of the National Earthquake Conference, (Memphis, Tennessee), Vol.II, pp. 81-90.

Bergamo G.,.Castellano M.G, Crespo M., Forni M., Gatti F., Karabalis D., Martì J., Novak H., Poggianti A., Silbe H., Strauss A., Summers P., S.Triantafillou. (2005). Guidelines for the application of passive control techniques in petrochemical plants. Bologna. Rapporto finale delle attività INDEPTH.

Calugaru, Vladimir; Mahin, Stephen A., (2009), Experimental and analytical studies of fixed-base and seismically isolated liquid storage tanks, 3rd International Conference on

Advances in Experimental Structural Engineering, October 15-16, 2009, San Francisco.
Ciampi V., De Angelis M., Paolacci F., (1995). "Design of yelding or friction based dissipative bracings for seismic protection of buildings", Engineering Structures, Vol.17 n°5, 381-391.
Ciampi V., (1998), A methodology for the design of energy dissipation devices for the seismic protection of bridges, U.S.-Italy Workshop on Seismic Protective Systems for Bridges, New York, 27-28 Apr. 1998
Christopoulos C., Filiatrault A., (2006), Principles of Passive Supplemental Damping and Seismic Isolation, IUSSpress, Pavia, Italy
De Angelis M, Giannini R., Paolacci F., (2010), Experimental investigation on the seismic response of a steel liquid storage tank equipped with floating roof by shaking table tests, Earthquake Engineering & Structural Dynamics, 39: 377-396. DOI: 10.1002/eqe.945
De Angelis M., Perno S., Reggio A., (2011). Dynamic response and optimal design of structures with large mass ratio TMD. Earthquake Engineering And Structural Dynamics. Published online (wileyonlinelibrary.com). DOI: 10.1002/eqe.1117.
Drosos J.C., Tsinopoulos S.V., Karabalis D. L., "Seismic response of spherical liquid storage tanks with a dissipative bracing system," 5th GRACM International Congress on Computational Mechanics, Limassol, 29 June-1 July, 2005, 313-319.
Erdik M. and Durukal E. (2000) ``Damage to and Vulnerability of Industry in the 1999 Kocaeli, Turkey Earthquake''.
European Committee for Standardization (CEN). Eurocode 8: Design of structures for earthquake resistance – Part 4: Silos, tanks and pipelines, 2003.
Fischer D. Dynamic fluid effects in liquid-filled flexible cylindrical tanks. Earthquake Engineering and Structural Dynamics 1979; 7: 587-601.
Fraraccio G., De Angelis M., (2006). Adjacent structures controlled by steel elastoplastic devices (In Italian). Ingegneria Sismica, Anno XXIII, N.2, maggio-agosto 2006.
Hamidi, M., El Naggar, M.H. . On the performance of SCF in seismic isolation of the interior equipment. Earthq Eng Struct D 2007;36:1581–604.
Haroun MA, Hausner GW. Earthquake response of deformable liquid storage tanks. Journal of Applied Mechanics 1981; 48: 411-418.
Hatayama K., (2008). Lessons from the 2003 Tokachi-oki, Japan, earthquake for prediction of long-period strong ground motions and sloshing damage to oil storage tanks. J Seismol (2008) 12: 255–263.
Hoang N., Fujino Y., Warnitchai P., 2008. Optimal tuned mass damper for seismic application and practical design formulas. Engineering Structures 30, 707-715.
Housner G.W., Bergman L.A., Caughey T.K., Chassiakos A.G., Claus R.O., Masri S.F., Skelton R.E., Soong, T.T., Spencer B.F., Jao J.T.P. (1997) "Structural Control: Past, Present and Future", ASCE J. of Eng Mech, 123, 897-971.
Housner GW. The dynamic behavior of water tanks. Bulletin of the Seismological Society of America 1963; 53: 381-387.

Johnson, G.H., Aschheim, M. and Sezen, H. (2000) ``Chapter 14: Industrial Facilities'' In Kocaeli, Turkey Earthquake of August 17, 1999 Reconnaissance Report. Earthquake Spectra 16 (Supplement A), pp. 311-350.

Kawasumi, H. (ed.) (1968) ``Introduction'' In: General Report on the Niigata Earthquake of 1964. Tokyo Electrical Engineering College Press, Tokyo.

Kilic, S.A. and Sozen, M.A. (2003) ``Evaluation of Effect of August 17, 1999, Marmara Earthquake on Two Tall Reinforced Concrete Chimneys''. ACI Structural Journal 100 (3), pp.357--364.

Marioni, A, (1998), The use of high damping rubber bearings for the protection of the structures from the seismic risk, Jornadas Portuguesas de Engenharia de Estruturas, Lisboa, LNEC, 25 – 28 de Novembro de 1998

Meyers R.A., (2004), Handbook of petroleum refining processes, McGraw-Hill handbooks, ISBN 0071391096, 9780071391092

Moulein, J.A. and Makkee, M. (1987) "Chapter 4: Processes in the oil refinery," Lecture notes for Proceskunde, TU Delft, The Netherlands, pp.1-60.

Nielsen, R. and Kiremidjian, A.S. [1986] ``Damage to Oil Refineries from Major Earthquakes'' ASCE Jnl Struct Eng 112 (6), pp.1481--1491.

Paolacci F, Giannini R., De Angelis M., Ciucci M., (2009), Seismic vulnerability of major-hazard industrial plants and applicability of innovative seismic protection systems for its reduction, 11WCSI, November 17-21, Guangzhou, China

Paolacci F., Giannini R., De Angelis M., Ciucci M., (2010). Applicability of passive control systems for the seismic protection of major-hazard industrial plants, Sustainable Development Strategies for Constructions in Europe and China, 19-20, Rome, Italy

Paolacci F., Giannini R., (2008), "Study of the effectiveness of steel cable dampers for the seismic protection of electrical equipment", 14 World Congress on Earthquake Engineering, Beijin, China

Reggio, A., De Angelis, M. . Feasibility of a passive isolation system with nonlinear hysteretic behaviour for the seismic protection of critical equipment. In: Proceedings of the XIV Covegno ANIDIS Associazione Nazionale Italiana di Ingegneria Sismica. Bari, Italy; 2011.

Renzi E., Perno S., Pantanella S., Ciampi V., (2007). Design, test and analysis of a light-weight dissipative bracing system for seismic protection of structures. Earthquake Engineering And Structural Dynamics. vol. 36, pp.519-539 ISSN: 1096-9845

Sakai F., Inoue R, (2008) Some considerations on seismic design andcontrols of sloshing in floating-roofed oil tanks, The 14th World Conference on Earthquake Engineering October 12-17, 2008, Beijing, China

Sakai F., Nishimura M., Ogawa H. Sloshing behavior of floating-roof oil storage tanks. Computer & Structures 1984, 19:1-2, 183-192.

Santagelo A, Scibilia N., Stadarelli R., (2007), Seismic Isolation of a tanks at Priolo Gargallo (in Italian), Giornate AICAP 2007, 4-6 Ottobre, 2007.

Showalter, P.S, Myers, M.F., (1992) Natural Disasters as the Cause of Technological Emergencies: A Review of the Decade 1980–1989, Working Paper #78, Boulder, Natural Hazards Research and Applications Information Center, Univ. of Colorado, Colorado.

Scholl, R.E. and Thiel Jr., C.C. (eds.) (1986) ``The Chile Earthquake of March 3, 1985 - Industrial Facilities'' Earthquake Spectra 2 (2), pp.373-409.

Sezen, H. and Whittaker, A.S. (2004) ``Performance of industrial facilities during the 1999, Kocaeli, Turkey Earthquake'' In: Proceedings of the 13th World Conference on Earthquake Engineering (Vancouver, Canada; Paper No. 282).

Sezen, H., Livaoğlu, R., Doğangün, A., (2008), Dynamic analysis and seismic performance evaluation of above-ground liquid-containing tanks, Engineering Structure, 30: 794-803

Spencer B. F., Nagarajaiah S., (2003). State of art of structural control. Journal of Structural Engineering, 129, 845-855.

Steinberg, L.J., Cruz, A.M., Vardar-Sukan, F. and Ersoz, Y. (2000) ``Risk management practices at industrial facilities during the Turkey earthquake of August 17, 1999: Case Study Report''.

Summers P., Jacob P., Marti J., Bergamo G., Dorfmann L., Castellano G., Poggianti A., Karabalis D., Silbe H., and Triantafillou S., 2004. Development of new base isolation devices for application at refineries and petrochemical facilities. 13th World Conference on Earthquake Engineering, Vancouver, B.C., Canada, August 1-6, 2004 Paper No. 1036.

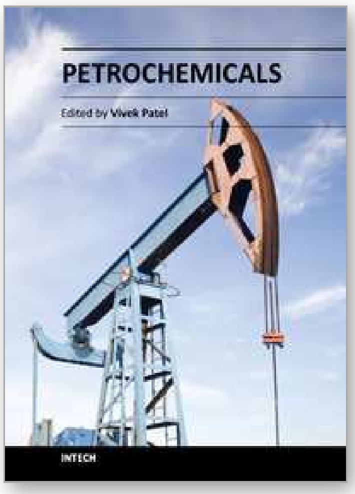
Suzuki, K., (2002) ``Report on damage to industrial facilities in the 1999 Kocaeli earthquake, Turkey'' Journal of Earthquake Engineering 6 (2), pp.275-296.

Suzuki, K., (2006), Earthquake Damage to Industrial Facilities and Development of Seismic and Vibration Control Technology – Based on Experience from the 1995 Kobe (Hanshin-Awaji) Earthquake – Journal of Disaster ResearchVol.1 No.2, 2006

Tajirian F. F., (1998), Base isolation design for civil components and civil structures, Proceedings of Structural Engineers World Congress, San Francisco, California, July

Vanmarcke EH, Gasparini DA. (1976). Simulated earthquake motions compatible with prescribed response spectra. Technical Report R76-4, Dept. of Civil Engineering, Massachusetts Inst. of Technology Cambridge, 1976-01, 99 pages (420/G32/1976).

Veletsos AS, Tang Y. Rocking response of liquid storage tanks. Journal of Engineering Mechanics 1987; 113: 1774-1792.




**Petrochemicals**

Edited by Dr Vivek Patel

ISBN 978-953-51-0411-7
Hard cover, 318 pages
**Publisher** InTech
**Published online** 28, March, 2012
**Published in print edition** March, 2012

The petrochemical industry is an important constituent in our pursuit of economic growth, employment generation and basic needs. It is a huge field that encompasses many commercial chemicals and polymers. This book is designed to help the reader, particularly students and researchers of petroleum science and engineering, understand the mechanics and techniques. The selection of topics addressed and the examples, tables and graphs used to illustrate them are governed, to a large extent, by the fact that this book is aimed primarily at the petroleum science and engineering technologist. This book is must-read material for students, engineers, and researchers working in the petrochemical and petroleum area. It gives a valuable and cost-effective insight into the relevant mechanisms and chemical reactions. The book aims to be concise, self-explanatory and informative.