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Problems and Perspectives in Seismic Quantitative Risk Analysis of Chemical Process Plants

Earthquakes represent a class of natural-technical (NaTech) hazards which in the past have been responsible of major accidents and significant losses in many industrial sites. However, while codes and standards are issued to design specific structures and equipment in both the civil and industrial domain, established procedures for seismic quantitative risk assessment (QRA) of process plants are not yet available. In this paper, a critical review of seismic QRA methods applicable to process plants is carried out. Their limitations are highlighted and areas where further research is needed are identified. This will allow to refine modeling tools in order to increase the capabilities of risk analysis in process plants subjected to earthquakes. [DOI: 10.1115/1.4040804]

Keywords: process plants, quantitative risk analysis, Na-Tech events, seismic vulnerability

1 Introduction

1.1 Background and Motivation. Besides process-related hazards, chemical process plants (CPPs) are vulnerable to natural hazards, such as earthquakes and hurricanes, which may trigger technological accidents usually referred to as natural-technological (NaTech) events, leading to equipment damage, release of dangerous substances, disruption of services and infrastructural, life, and economic losses [1]. The tremendous impact of NaTech events was demonstrated by the recent Tohoku earthquake and the following Fukushima disaster in 2011. The problem is quite relevant as up to 5% of industrial accidents, involving the release of dangerous substances, which are triggered by natural hazards [2]. A major natural hazard for process plants is undoubtedly seismic events which, therefore, have to be systematically included in current risk assessment procedures. The problem is especially relevant for plants classified as major-risk facilities according to the Seveso-III Directive [3], which regulates the control of major accident hazards involving dangerous substances. The Seveso-III Directive does not explicitly consider natural hazards, even though thousands of major-risk European facilities are located in areas of medium to high seismicity and often near population centers. As a result, there are several open research questions related to quantitative risk assessment (QRA) for CCP. Recalling that QRA represents an analytic evaluation of risk by rigorous, replicable methods evaluated under agreed protocols of an expert community and peer-reviewed to verify the underlying assumptions, some of these questions are listed herein:

- The existing procedures for QRA of process plants, including nuclear ones, cannot adequately account for the impacts of natural hazards. In fact, Na-Tech events often represent a common cause leading to the simultaneous occurrence of several interacting faults, which can often interfere with rescue operations. Conversely, the traditional QRA of process plants starts with the analysis of a single failure or a loss of containment (LOC) in a single equipment; in this situation, it is much easier to define a few logic models (event trees and fault trees) representing accident dynamics.
- To facilitate probabilistic Na-Tech risk analysis, some methodologies have been recently proposed. These are based on the estimation of on-site natural hazard parameters, the determination of damage probabilities of plant units, and the assessment of probability and severity of potential Na-Tech events [4]. Nonetheless, these analyses usually rely on approximate fragility curves and equipment damage models, which were largely evaluated in the sixties [5], and, therefore, are not suitable for more recent equipment.
- Critical components like tanks, pipe elbows, and bolted flanges exhibit unusual and very complex phenomena. For instance, local wall thinning in pipe elbows is caused by mechanisms such as flow-accelerated corrosion and liquid droplet impingement erosion; for these reasons, wall thickness inspection is required and difficult to perform. FE modeling to detect wall thinning or local flaws and on-site system identification based on dynamic testing is still a challenge, and requires long inspections or large computing time [6].
- Chemical process plants can be thought as part of the network of infrastructures, characterized by high consequence risk of complex systems with limited knowledge behavior. As such, resilience has emerged as a fundamental concern

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for researchers, users, and system managers. To quantify resilience of complex systems, both conceptual frameworks based on robustness and recovery rapidity as well as resilience indices have been recently proposed [7]. These formulations are powerful in studying postevent recovery and can be used to rank the inventory of damaged structures. Nonetheless, they cannot be easily translated into simple procedures that can be incorporated in the structural analysis/design process. These are some of the issues that have been raised over the years.

1.2 Scope. In this paper, we will attempt to critically revisit seismic QRA methodologies and some of the abovementioned issues relevant to CCPs. Technical details of different issues will be presented only to the extent necessary to analyze and judge key strengths and weaknesses, and suggestions will be offered on ways to address future research.

2 Operational Steps in Seismic Quantitative Risk Assessment for Chemical Plants

Seismic QRA methods are well established both in the civil and industrial sector [8–11]. Nevertheless, as compared to other civil infrastructures (i.e., buildings, bridges, and highways) or specific types of industrial plants such as nuclear power plants (NPPs), CPPs exhibit specific features which ask for dedicated seismic risk assessment methodologies, synthetized herein:

- A large number of process equipment are distributed over a wide geographical area instead of being concentrated in a few single structures.
- Each process equipment may store relevant amount of hazardous substances. LOC events from equipment can trigger chains of accidents propagating in a domino-like fashion consequent to physical effects (thermal radiation, overpressure, fragments projection, and equipment collapse) from released materials and energy.
- Apart from indirect equipment interaction via energy release, equipment may be physically connected through pipes and supporting structures. LOCs may also occur along pipe paths, thus representing a linear source potential. Consequently, seismic QRA limited to major process unit only may not be sufficient.
- Simultaneous and independent damage of equipment caused by seismic excitation can give rise to a combinatorial multiplicity of starting scenarios leading to multiple interacting chains of accidents [12], where the ending scenario is not predetermined.

As a result, it is not feasible to represent the entire spectrum of consequences at the entire plant level with a few event trees, as happens, for instance, in the case of NPPs. In CPPs, there is not a single critical top event to be analyzed and damage scenarios must be dynamically generated. In fact, while the initial LOC event is assigned in traditional QRA of process plants, in the case of seismic QRA, it is the result of interaction between seismic excitation and equipment structure. As a consequence, standard data for LOC frequencies commonly used for QRA in process plants cannot be used, because they do not refer to seismic events. In this respect, fragility functions of critical components are usually employed to evaluate the damage and the corresponding LOC frequency.

Therefore, it can be easily recognized that traditional seismic QRA methods developed for civil buildings and NPPs may not be directly applicable to the case of CPPs because the corresponding methods do not allow the above issues to be dealt with in a suitable manner. As an example, in Ref. [13], the authors discussed multicomponent failure scenarios due to natural disasters and evidenced how the risk of a multi-unit plant due to natural events can highly differ for a classical QRA, highlighting the key role of domino effects.

Moreover, a proper seismic QRA requires different research communities to interact, i.e., structural engineers and safety analysts, who operate at different conceptual scales, respectively, micromeso and meso-large, with different intrinsic levels of uncertainty ranges and information details. In fact, the seismic response is assessed for single process units at the level of structural analysis, either using detailed numerical or experimental methods, allowing for computation of both stresses and strains in structural members, or using macroscopic physical effect simulation and statistical damage correlations such as dose-response Probit functions [14–16], for loss estimation and accident propagation which are carried out at the system level.

Based on the aforementioned discussion and existing literature guidelines [17–20], the operational steps in a seismic QRA procedure for CPPs should include the following steps, where (a) through (c) are of preparatory nature, whereas steps (d) through (i) are the actual operational steps [19,21]:

(a) Classification of plant equipment and process units into few critical categories and identification of specific limit states (LS) and failure modes triggered by earthquake exposure; see, in this respect, Sec. 3.
(b) Characterization of the seismic hazard input providing the mean annual frequency of exceeding a predefined intensity level of seismic excitation, and selection of input ground motions according to site-specific geological conditions; see Sec. 4.
(c) Derivation of seismic fragility curves for critical equipment, which provide the probability of exceeding relevant structural limit states for a given seismic input intensity, see, in this respect, Sec. 5.
(d) Establishment of rules to associate the LOC probabilities to damage states (DS) as discussed in Sec. 6.
(e) Generation of starting scenarios based on fragility curves. As an alternative, a credible reference damage scenario can be arbitrarily chosen.
(f) Quantification of LOC events for the triggering units damaged by the earthquake, which includes estimation of source terms and physical effects for each starting scenario.
(g) Consequence-based analysis of the identified starting scenario(s), with the assessment of propagation paths, which included the interacting chains of accidents triggered by the earthquake and the occurrence probability associated with each scenario as presented in Sec. 7.
(h) Estimation of damage probability and related fatalities and economic losses associated with the equipment, individuals, and society, as discussed in Sec. 8.
(i) Risk estimation and ranking of scenarios as described in Sec. 8.

In the following, all the abovementioned steps are discussed in depth with the identification of limits to current practice and potential future developments toward an approach that includes a systematic evaluation of the most critical starting damage scenarios and the related cascading effects (domino effects), providing also a proper risk metric for the decision making analysis.

3 Structural Classification of Process Plant Equipment

Process industry relies on a large number of basic operations and equipment. Nevertheless, critical units can be easily collected in a limited number of categories, based on both structural and functional characteristics [22,23]. This line of action represents an important aspect of the seismic QRA because it entails the characterization of the structural performance of all critical equipment and the identification of possible LOC events, both necessary for damage propagation analysis.

The experience of both structural and industrial engineers derived by postearthquake inspections helps to consolidate this knowledge with the identification of the most common damage types and relevant consequences. Detailed information on the behavior of the process plant components during past seismic events are available in literature databases (ICHEME, major accident reporting system, major hazard incident data service). Based on these data, the main equipment of a process plant can be classified into a restricted number of categories [24]: (a) slim vessels, (b) above-ground squat equipment, (c) squat equipment supported by columns, and (d) piping systems.

Cylindrical vessels belong to the first category, which have a high height-to-diameter ratio, typically between 5 and 30, and can be classified into the following subcategories: (1) vertical cylindrical vessels, which are directly anchored to the foundation and not restrained along the height. This category includes distillation columns and reactors. The distribution of mass along the height is usually rather uniform and may be considered continuous, even though some internal discontinuities could be present; (2) highly slender vertical vessels, which are usually constrained both at the foundation and at specific points. This group includes very slim columns such as stacks and flares. Their mass is entirely associated with the structure itself, because they contain only atmospheric pressure gas; and (3) horizontal cylindrical vessels, which are supported by two or more saddles connected to the foundation platform. In this category, many pressurized storage tanks and shell-and-tube heat exchangers are included.

The main damages of slim vessels are located at the transition zones between shell and skirt, and at foundation connections. In fact, the slim vessels are subjected to both yielding at the skirt, see Fig. 1 [25], and partial pull-out of anchor bolts [26,27], as illustrated in Fig. 2.

However, loss of contained fluids caused by failure of connected flanges due to excessive relative displacements is not excluded [17]. The first case may cause the entire collapse of the structure, even though it can be considered as a rare event [28]. Horizontal vessels could experience similar problems at the connection with the supporting saddles showing a non-negligible seismic vulnerability, as analytically demonstrated in Ref. [29]. The detachment of the connected pipes and, consequently, the release of the content could also occur [30].

Large cylindrical steel storage tanks well represent the second category. They are characterized by aspect ratios ranging between 0.2 and 2. The roof can be welded to the shell (fixed conical roof) or floating over the contained liquid. The operating volume varies from some tens to 200,000 m^3. The typical damages associated with these structures are related to buckling phenomena of the wall (elephant foot buckling and sloshing buckling, depicted in Figs. 3 and 4 [31]) or with failure of the bottom plate—wall joint

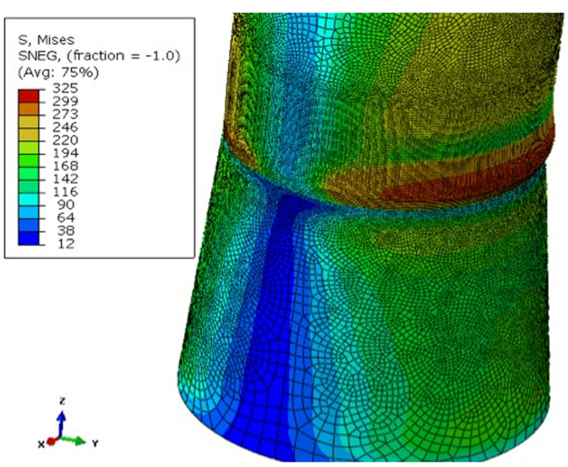

Fig. 1 Buckling phenomenon in the skirt at a column base [25]

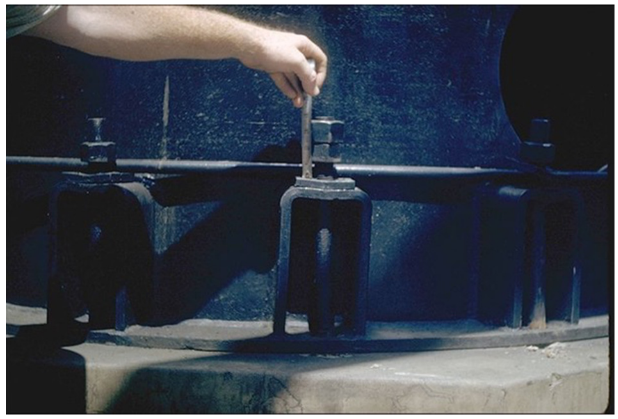

Fig. 2 Residual deformation of the anchor in the column skirt [25] (Reproduced from https://nisee.berkeley.edu/elibrary/Image/S116)

Fig. 3 Elephant foot buckling failure of 2000 m^3 water tank [31]

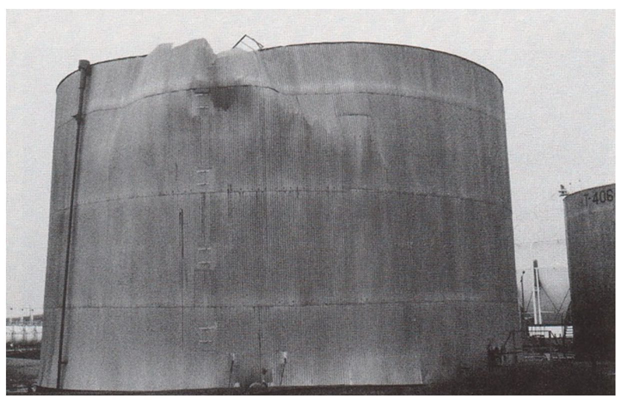

Fig. 4 Sloshing buckling failure of a water tank [31]

or the detachment of the pipes as shown in Fig. 5, due to uplifting or sliding phenomena [32–35].

Other damages and accidents are related to excessive sloshing motion, especially in the presence of floating roof [36,37], which can cause liquid overtopping and fire due to the crash between roof itself and the wall. For example, during 1999 Izmit and 2003 Tokachi-Oki earthquakes, most of the tanks were destroyed due to excessive sloshing motion (Fig. 6 [38]). The occurrence of these damage states can result in LOC events with different degrees of severity [39].

The third category includes (1) spherical storage vessels, which are essentially used for pressurized liquefied gases. They generally are elevated above ground using steel columns placed along the

Fig. 5 Motor fuel storage tank slid off its foundation causing extensive damage to inlet and outlet piping [32] (Reprinted with permission of Earthquake Engineering Research Institute © 2002)

Fig. 6 Damages to tanks with floating roof due to Tokachi-Oki earthquakes [38] (Reprinted with permission from Springer Nature © 2007)

Fig. 7 LPG tank failure during the 2011 Tohoku Earthquake [40]

circumference, welded to the shell at the equatorial level and usually linked to each other by diagonal braces; typical damages are related to the leg breakage depicted in Fig. 7 [40]; (2) large vertical storage vessels for cryogenic liquefied gases (i.e., LNG); their configuration is similar to that of the large atmospheric storage

Fig. 8 LPG tank failure during the 2011 Tohoku Earthquake [41] (Reprinted with permission of Elsevier © 2000)

vessels for liquids previously mentioned, with double shell construction, including thermal insulation. Their bottoms are anchored to concrete plates, supported by short reinforced concrete columns illustrated in Fig. 8 [41]. Other tank variants can be found in Ref. [42].

Process furnaces and steam boilers are units employed to heat or vaporize large amounts of liquid products according to the chemical process demand. Process furnaces are structures with generally large size, with a few standardized shapes, mainly cathedral-type and vertical cylinders. These furnaces are kept elevated from the ground by means of short columns, usually reinforced concrete columns, according to the location of burners that require pipes and space for maintenance. For these components, the collapse is mainly due to the soft-story phenomenon caused by shear failure of short columns. The collapse of chimneys is also possible as well as the detachment of pipes and of the internal liners.

Pipelines, the fourth category, connect all equipment involved in the process, transferring the fluids within the plants. In a large refinery, hundreds of kilometers of pipelines of different size are installed, and they are mainly constructed using steel, but in some cases ceramics, glass, concrete, etc., may be used when a specific corrosion proof characteristic is required. Metallic pipes themselves are not particularly vulnerable to seismic actions, but they can suffer the effects of anchor motion, which may not be compatible with pipe deformations [43].

The abovementioned framework offers an easy guideline to identify the most critical units installed in process plants along with main damages related to earthquakes. This is particularly useful to identify the criticality concerning loss of containment and damage propagation effects discussed at length in Sec. 7. Similarly, the main issues related to the quantification of damage level and LOC are analyzed in depth in Sec. 6.

4 Seismic Hazard and Input Selection for Process Plants

The huge structural damages caused by strong earthquakes, such as in the 1989 Loma Prieta, the 1994 Northridge, the 1999 Chi-Chi, Taiwan, the 1999 Kocaeli and 2011 Tohoku, Japan, earthquake [44–46], demonstrate that a dependable evaluation of seismic hazard appears of paramount importance.

The definition of the levels of earthquake motions to be considered for analysis requires a special attention. In fact, several standards dealing with seismic analysis of process plant components, e.g., NFPA 59A [47], in view of enhanced performance and damage limitation, use the same seismic hazard definitions adopted by nuclear standards NEA/CSNI/R (2007)17 [48]. These standards prescribe two different limit states, namely the operating basis

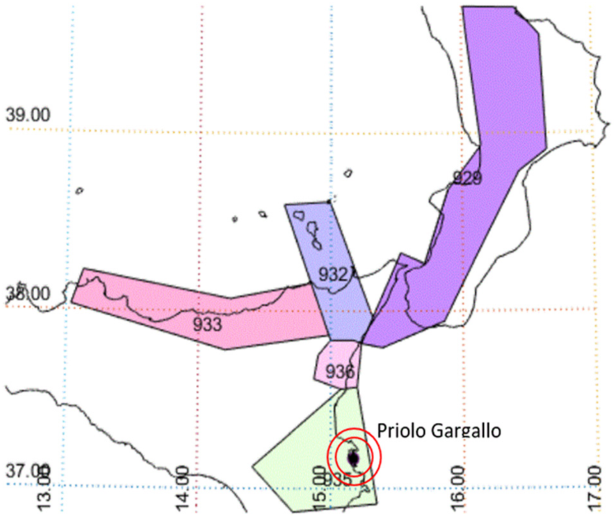

Fig. 9 Seismogenic zones and site: Priolo Gargallo (Italy)

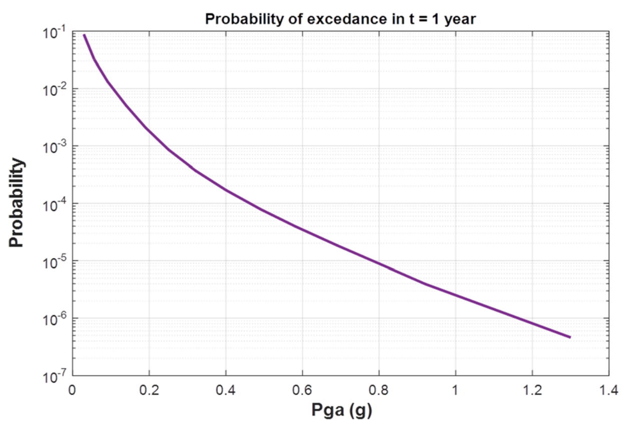

Fig. 10 Example of Hazard curve of Priolo Gargallo, Italy

earthquake and the safe shutdown earthquake. Nevertheless, intended safety objectives are different: in fact, (i) conventional facilities are designed for human lives protection and damage limitation [49]; conversely, (ii) NPPs rules enforce integrity and functionality of structures systems and safety-critical components; as a result, inelastic behavior is not allowed.

Thus, in moderate seismicity regions, a correspondence between the 10% probability of exceedance in 50 years, i.e., 475 years return period used in Eurocode 8 and the operating basis earthquake ground motion defined in nuclear standards, can be established. Increased return periods can be achieved through importance factors. Safe shutdown earthquake ground motion is usually defined according to rules properly defined for NNP industry. Therefore, the definition of the corresponding return periods for the design/assessment of process plants is more involved [50].

In any case, a full probabilistic seismic hazard analysis (PSHA) of the site is necessary. The procedure for assessing the PSHA of a facility is not significantly different from that used, for example, for assessing the seismic risk of buildings, whose highlights still follow the methodology proposed by Cornell [51]. The hazard analysis provides the probability of exceeding a selected intensity measure (IM) value in a given time interval as indicated in Figs. 9 and 10. The obtained hazard curves take into account all contributions coming from different levels of magnitude (M) and distance (R) through attenuation functions. The disaggregation analysis [52,53] is then used to separate these different contributions.

However, when the seismicity is modeled using two-dimensional sources, the disaggregation provides the trivial result that the maximum contribution is given by an event generated in proximity of the site [54].

Attenuation functions' ground motion predictive equations (GMPEs) are generally obtained on the basis of statistical analyses using multiple station recordings placed at different sites. Moreover, site effects are grossly taken into account by grouping sites in a few classes, with a similar value to the 30-m velocity (versus 30). Obviously, this leads to an increase in GMPE dispersion that could significantly affect risk assessment. For extremely critical facilities, the use of GMPE derived from one station has been proposed [55]. However, this represents an additional difficulty, as it assumes that a seismic recording station is installed at the site of interest since long time and that the station collected a statistically significant sample, particularly in the high intensity range. Atkinson [56], estimated a reduction in GMPE standard deviation to about 90%. However, this reduction should be accompanied by a more accurate assessment of the site effects [57].

For the construction of fragility curves, it is often necessary to use nonlinear analysis, which requires seismic motion records [58]. If a scalar IM is used, such as the peak ground acceleration or spectra acceleration at the fundamental period (Sa(T)), the correlation with the response, expressed in terms engineering demand parameters (EDP), is generally low as shown in Fig. 11(*b*) [59]. Thus, in addition to the uncertainty of the attenuation law, a further uncertainty is introduced. Similar remarks can be made if the ground motion records are selected on the basis of given range of frequencies usually provided by a target uniform hazard spectrum (UHS); see, in this respect, Fig. 11(*a*) [60].

As an alternative, accelerograms whose spectrum individually matches the UHS could be used. These records can be artificially built, or obtained by modifying, with appropriate techniques, the frequency content of records. The first approach has been completely abandoned, while the second one still represents an interesting alternative [61,62].

To reduce the dispersion of the response without modifying the spectral content of the records, Shome et al. [63], proposed to use

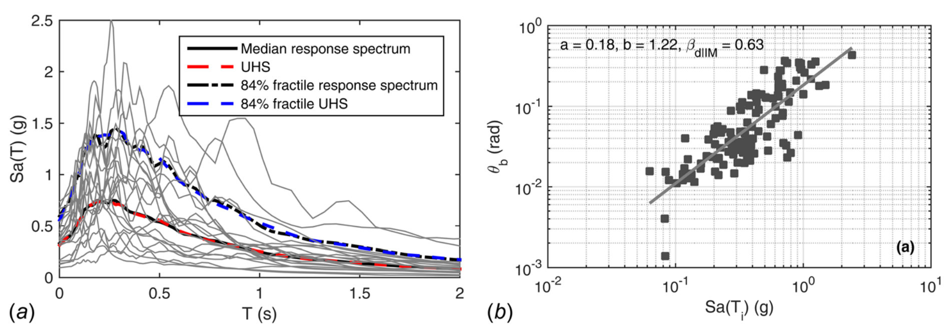

Fig. 11 (*a*) Selection of natural records based on UHS and (*b*) example of EDP (q)—IM (Sa) relationship [59]

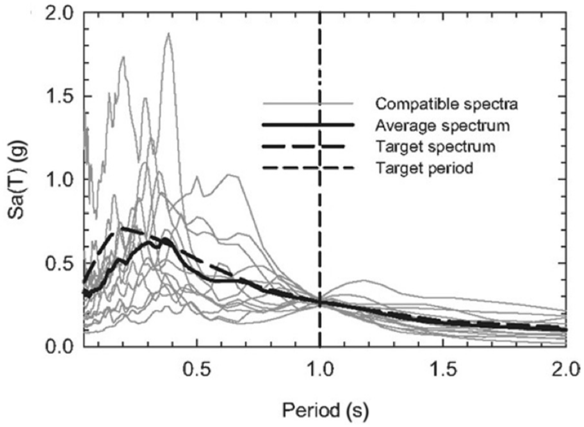

Fig. 12 Scaling of the accelerograms based on the spectral ordinate at the fundamental period [64]

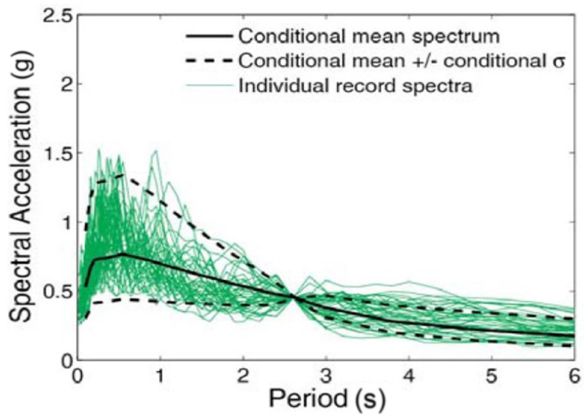

Fig. 13 Scaling of the accelerograms based on the CMS [66] (Reprinted with permission from ASCE © 2011)

the response spectrum at the most significant vibration period of the structure as IM, as depicted in Fig. 12. This criterion works properly only if the structural response depends mainly on one vibration mode and behaves elastically. To overcome this approximation, Cornell and Baker proposed to use the conditional mean spectrum (CMS), which is obtained by taking into account the correlation between the variables that account for the dispersion of the response spectrum at different periods T_i [64–68]. The accelerograms are then selected so that the average of their spectra approximates the CMS and their dispersion is contained within the CMS $\pm$ 1 standard deviation σ, as illustrated in Fig. 13.

However, process plant components are often characterized by a variegate frequency content. Therefore, the above record selection criteria could poorly fail. For example, storage tanks, which are among the most vulnerable components of a process plant, exhibit at least two significant different natural periods, due to impulsive and convective motion, respectively. This clearly complicates the problem of the accelerograms selection. In civil engineering, where complex constructions exhibit similar problems, vector-valued IMs have been defined [69]. However, in many applications, this approach shows a limited effectiveness, whereas a much more complicated procedure is required by including the necessity of performing a vector PSHA [70].

5 Fragility Curves Estimation of Process Plant Components

Seismic vulnerability of structures and equipment is traditionally expressed in the form of fragility curves. The fragility curve of a component provides the probability of exceedance P_f of a certain limit state as a function of selected EDPs conditioned on a particular IM of input (peak ground acceleration, spectral acceleration at fundamental period, etc.)

$$P_f(\mathrm{IM}) = P[\mathrm{EDP} \geq \mathrm{LS} \,|\, \mathrm{IM}] \quad (1)$$

The main issues in evaluating Eq. (1) are essentially related to four distinct aspects: (a) definition of reliable numerical models of critical units accounting for all possible sources of nonlinearity, typically present in the case of earthquakes; (b) the definition of seismic hazard-consistent input signals for the assessment of the nonlinear seismic response of critical units and selection of proper IMs, discussed in Sec. 4; (c) selection of a set of representative EDPs and EDP-consistent DS along with the corresponding LS; and (d) selection of proper fragility analysis methods.

As far as item (a) is concerned, in order to define appropriate numerical models of critical apparatuses described in Sec. 4, many contributions are available in the literature. However, a particular attention has been recently paid to the modeling of liquid storage tanks and piping systems for their recognized importance in the seismic vulnerability assessment of process plants.

About storage tanks, starting from the earliest work of Housner [71], the problem of the seismic modeling has been mostly treated using lumped mass models [72]. The problem of including nonlinearities due to uplifting, when unanchored tanks are considered, has also been analyzed through simplified models, as shown in Fig. 14 [73–75].

Three-dimensional FEM models have been recently proposed, see Fig. 15 after Phan et al. [76], among others, but their complexity and the computational effort required for running analyses

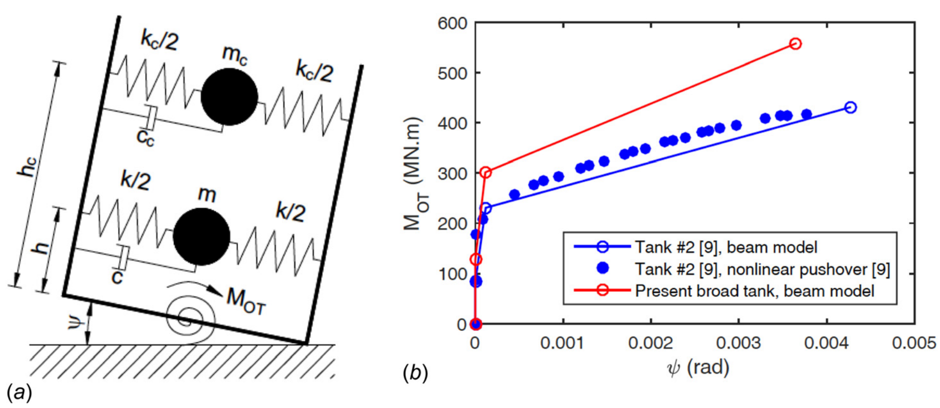

Fig. 14 (a) Numerical model of unanchored storage tanks and (b) constitutive law of the rotational spring

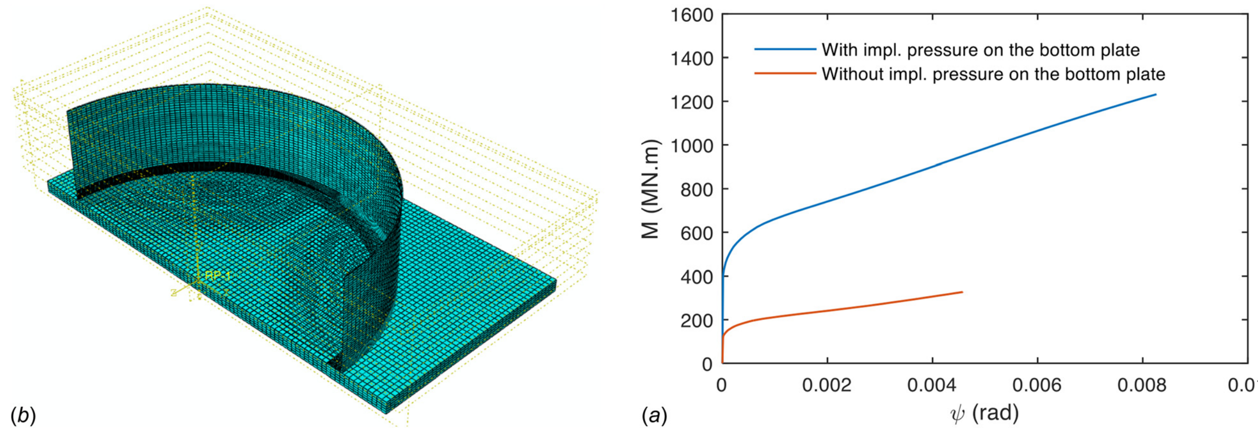

Fig. 15 (*a*) ABAQUS model of an unanchored tank and (*b*) static pushover analysis results of the tank: (*a*) overturning moment-rotation (*M*–ψ) relationship [59]

make them not suitable for fragility evaluation, where usually a large number of simulations are needed.

For piping systems, a large number of works have been devoted to the numerical modeling in seismic conditions [77,78]. Nonetheless, proper models for fragility analysis, where the explicit nonlinearities of pipes and fittings are included, are rather limited [79]. An important aspect of the problem is the dynamic interaction with the support structure that often is not accounted for, but that can strongly influence the seismic response of pipes [80,81]. In this respect, the definition of the seismic action at pipes level and in particular of floor response spectra is currently under investigation. Approaches in which multisupport excitations are considered have also been proposed [82].

The definition of proper EDP and EDP-consistent DS represents another delicate aspect of fragility analysis. However, a limited number of contributions have been offered in the literature. For example, an interesting contribution by Vathi et al. [83] provides performance criteria for the design of storage tanks and piping systems, identifying the most critical failure modes, the EDPs and LS, for each structural category. These performance criteria could be profitably used for fragility analysis.

Fragility analysis of storage tanks has been widely investigated in the past by using different strategies. An empirical method to develop seismic fragility relationships can be found in Salzano et al. [84], where the damage classification defined in HAZUS manual was adopted. Furthermore, Berahman and Behnamfar [85] proposed a Bayesian approach for the seismic fragility analysis of unanchored on-grade steel storage tanks. This approach based on historical data and American Lifeline Alliance tanks database [86] properly accounted for epistemic as well as aleatory uncertainties. More precisely, aleatory uncertainties reflect our inability to predict random observable events, whereas epistemic uncertainties represent the analyst lack of knowledge of values of parameters, probabilities, failure rates, etc., that are used in the model of a seismic QRA. The analytical approaches, which use both time history analyses and probabilistic seismic methods, have also been adopted in recent studies. Fragility curves for the elephant's foot buckling failure mode were developed by means of incremental time-history analyses [87,88].

Moreover, a rational procedure for the seismic vulnerability assessment of storage tanks was defined by Iervolino et al. [89], where the fragility curves were derived by the response surface method. Recently, a comparison of the cloud analysis and the incremental dynamic analysis is carried out in Ref. [90] for the seismic vulnerability assessment of an existing elevated tank, see Fig. 16, where the seismic demands including the lateral displacement of the support structure and the compressive meridional stress in the tank wall are investigated.

Works dedicated to fragility analysis of piping systems are less frequent. A system-level fragility method to evaluate seismic fragility of threaded Tee-joint connection in typical hospital piping system can be found in Bu and Abhinav [91], where damage states were defined from multiple time history analysis using a Monte Carlo simulation. Furthermore, a simplified fragility analysis procedure of a NPP piping system was carried out by Ehsan et al. [92], where the most critical section of the system was identified as the elbow and the fixed point.

However, a few contributions on fragility functions have been presented for piping systems of different industries except refinery plants. A specific contribution devoted to a typical refinery piping system has been provided by Caprinozzi et al. [93]. All contributions are based on a component-level approach. However, a more accurate approach would require a system-level analysis not available yet in the authors' knowledge.

According to Eq. (1), a fragility curve strongly depends on the IM adopted. However, a limited number of contributions suggesting the proper IM for each critical component of a process plants are available. For example, Phan and Paolacci [94] studied the efficiency and the sufficiency of the most used IMs for fragility analysis of storage tanks. An IM is efficient when the dispersion of the selected EDP is suitably low. Differently, the IM is sufficient when the variability with the seismic hazard parameters, M and R, is limited. The relevant outcomes highlighted the difficulties in using scalar IMs for storage tanks because of the presence of two different and distant vibration modes (impulsive and convective). In this respect, vector-valued IMs (a vector of IMs) are certainly more suitable, even though no contributions on this aspect have been published.

Despite the increasing interest in fragility analysis for the most critical units of process plants, i.e., storage tanks and piping systems, there is still an evident lack of knowledge in many of the aspects previously identified. Therefore, additional research is needed and expected to fill the gap in the definition of nonlinear models, limit states, and IMs.

6 Damage States and Loss of Content in Critical Units Under Seismic Loading

Damage states in the components of a process plant, when subjected to seismic loading, can induce a certain degree of LOC of the stored substance with possible consequences, i.e., fire and explosion, to surrounding units and community. This aspect is particularly crucial for the seismic QRA of industrial plants, where a correct evaluation of consequences is at the base of the effectiveness of the procedure. While the analysis of structural effects on process equipment caused by seismic excitation is fairly established, thanks to research on structural fragility, a further major issue in seismic QRA of CPPs lies in estimating damage

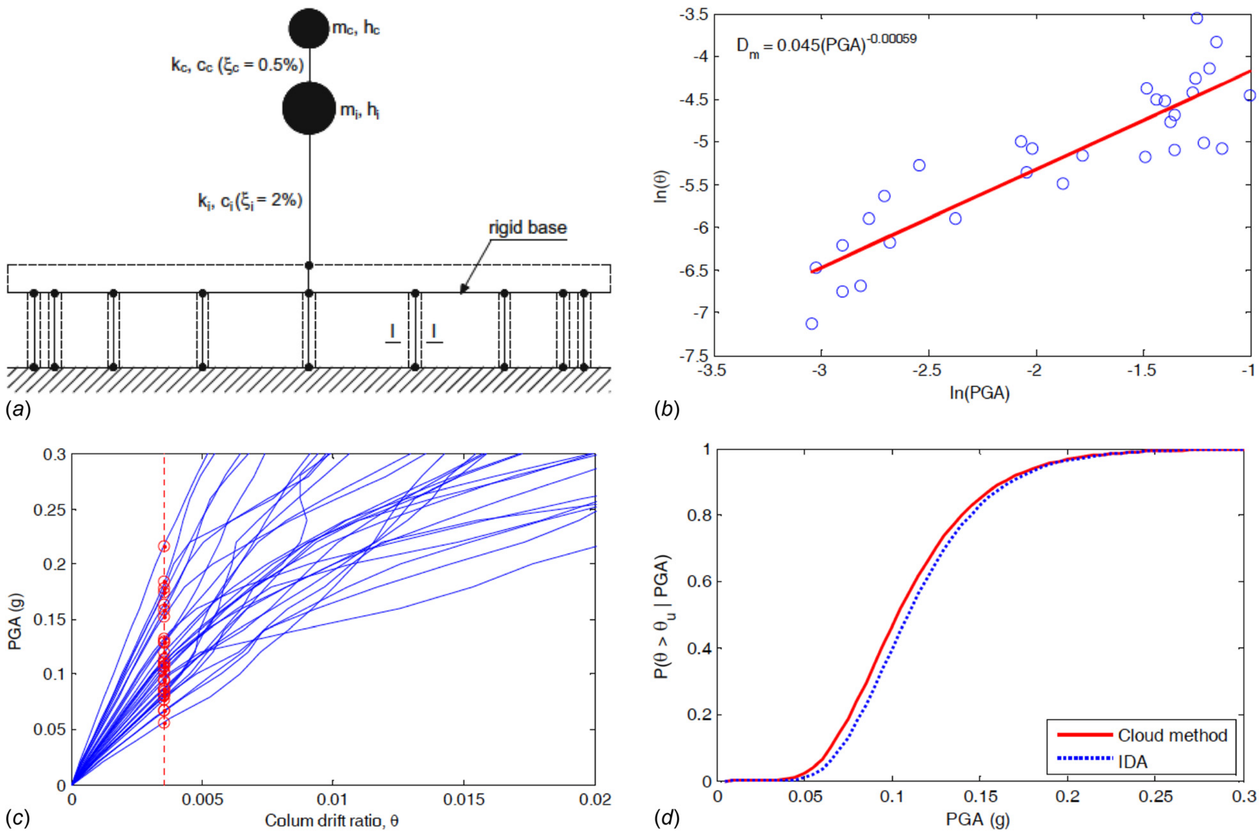

Fig. 16 (*a*) Fragility analysis of an elevated tank [72] and [90], (*a*) numerical model, (*b*) cloud analysis results, (*c*) incremental dynamic results, and (*d*) fragility curves

propagation through chains of accidents triggered by release of hazardous materials and energy from seismically damaged units.

Three main issues concur to analyze damage and resulting uncertainty propagation, namely, (a) the estimation of LOC event subsequent to seismic damage; (b) the generation of chains of accidents; and (c) the estimation of target equipment vulnerability which propagates the chains of accidents.

As far as LOC generation is concerned, it should be pointed out that traditional QRA relies on the assumption of conventional LOC events, i.e., instantaneous release of the complete inventory; continuous release of the complete inventory in 10 min at a constant rate of release; and continuous release from a hole with an effective diameter of 10 mm, occurring with a predefined frequency. Such LOC events are related to internal failures only, such as human error or equipment failure, and neglect structural collapse or external events, which is commonplace in the case of natural hazards. Instead, in seismic QRA, the actual LOC events should be correlated to structural damage of the equipment resulting from seismic excitation.

In this respect, the European project INDUSE [25] was specifically dedicated to the evaluation of the behavior of industrial components under seismic loading, allowing for data provision for the quantification LOC events for given response parameters. In particular, specific tests were conducted on pipes, pipe fittings (joints, elbows), and nozzles [25,30,50,95]. Concerning storage tanks, no specific experimental activity was recently conducted in Europe for the determination of DS/LOC relationships, except some tests performed within the European project INDUSE-2-SAFETY [96], whose results, see, for instance, Fig. 17, are still under evaluation.

Some experimental tests were also performed in Japan and U.S. [33], which confirmed a certain over-conservatism of the current codes in assessing the buckling phenomenon. In addition, only few of them identified leakage conditions under buckling of the tank wall, especially for elephant foot buckling.

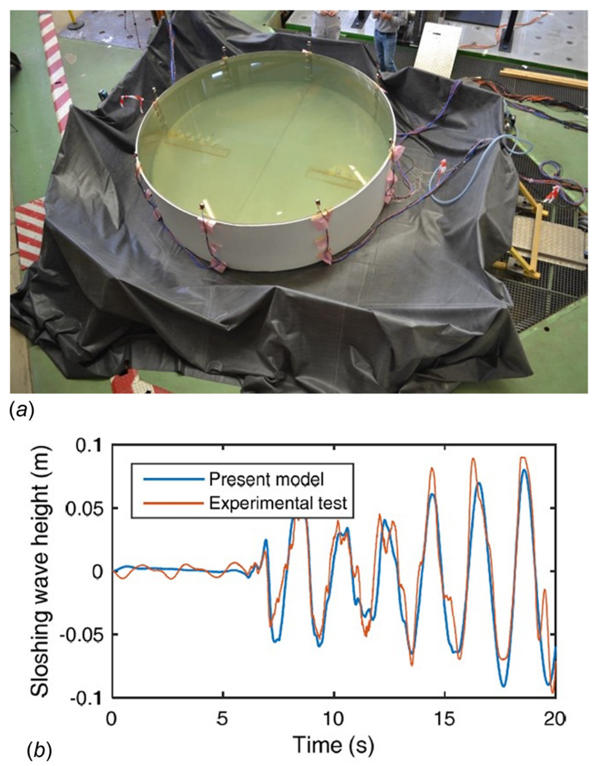

Fig. 17 Shake table test on a broad tank within the European project INDUSE2: (*a*) picture of the mock-up and (*b*) numerical-experimental comparison of the sloshing wave [76]

Table 1 LOC events and DS for unanchored tanks (LS/LOC matrix) [101]

DS	EDP	LS	LOC1 continuous release from a 10 mm hole	LOC2 continuous release from a full bore of the pipe	LOC3 instantaneous release of full content
Elephant foot or diamond shape buckling	Meridional stress σ_M	Buckling limit σ_{EFB}	Yes	Yes	No
Tensile failure of the wall	Hoop stress σ_H	Tensile strength σ_E	Yes	No	No
Sliding	Total base shear	Sliding force $F_{\text{sliding}} = \mu W$[a]	No	Yes	No
Overturning	Overturning moment	Overturning moment limit	No	No	Yes
Base plate fracture	Max local strain	Strain limit	No	No	No
Roof damage	Max vertical displacement of liquid	Free-board height	No	No	No

[a] μ = friction coefficient between tanks and foundation, W = total weight of the tank.

Up to now, fragility curves directly providing the probability of occurrence of LOC as a function of the earthquake intensity measures are not yet available. Moreover, fragility curves stated in terms of structural limit states [97] cannot be directly associated univocally to a type of LOC, given that the same LOC could be determined by different limit states. Therefore, simplified methods have been used until now. For instance, Refs. [17], [39], and [98] do not refer to structural limit states but rather consider broadly defined damage states (i.e., no, slight, moderate, extensive damage, and total collapse) following O'Rourke and So [99] and HAZUS classification [5], being such states probabilistically correlated to the seismic intensity measure through fragility curves. The damages states are then deterministically associated with release classes, i.e., no or negligible loss; slight or moderate loss; consistent and rapid LOC.

A LS/LOC matrix has been instead used in Refs. [100] and [101]. This matrix deterministically correlates predefined LSs and LOC categories, but allows associating a LOC with multiple LSs and vice versa. Each LOC probability is then computed on the basis of the cumulative probability of occurrence of the nonmutually exclusive corresponding LSs [100] or by Monte Carlo sampling [101]. An example of matrix for unanchored storage tanks is presented in Table 1, where LOCs 1, 2, and 3 are the conventional loss of containment defined for the classical quantitative risk analysis [102].

Very recently, Bursi et al. [42] proposed an analytical approach for the identification of a failure condition in flange bolted joints associated with LOC, which is based on experimental outcomes.

From the above illustrated framework, it is clear, that, in the light of seismic QRA, an important effort is still needed to identify a possible way for the evaluation of reliable DS/LOC relationships in critical units of a process plant.

7 Effects of Damage Propagation

Damage propagation modeling in seismic QRA does not differ conceptually from domino accident chains analysis which is well established in QRA of CPPs. See, for instance, recent reviews in Refs. [103–105]. However, two notable specific issues apply: effect propagation may act on structures already weakened by seismic excitation and superposition of physical effects may apply when an equipment is involved by two or more distinct chains of accidents. Both of the aforementioned problems have not yet been fully analyzed in the literature.

In Domino chains propagation modeling, two different approaches are used. In one case, the intensity of physical effects emanating from a source unit is computed at the location of the potential target units and Probit curves are used to assess the damage probability of the target equipment. In the other case, a conventional damage zone, bounded by the locus of points where a conventional threshold value of effect intensity is reached, is at first determined [106–109]. Then, all units within the damage zone are considered to be damaged.

Damage propagation is usually modeled in iterative manner by assessing which nearby target units can be damaged by each source unit while the accident chain advances. In the case of seismic QRA, the procedure starts from the units damaged by a seismic record. This propagation is schematized in a discrete stepwise fashion given that a target unit can subsequently act as a source unit to propagate damage to further undamaged units. Propagation of the chain of accidents stops when no further unit can be damaged or when a predefined number of propagation steps (usually two) have been reached. Propagation modeling may follow in a systematic enumerative manner [17,20,110,111]) or by Monte Carlo sampling [101,112]. An example of seismic accidental chain of a refinery tank farm, determined by Monte Carlo simulations, is illustrated in Fig. 18. Recently, graph theory has also been suggested for propagation analysis [113–115]. Physical effects generation is usually carried out resorting to event trees, see Fig. 19, specific of each target unit [116,117].

As pointed out earlier, vulnerability of target units subjected to physical effects from source units is usually assessed in probabilistic manner using Probit curves. Nevertheless, available Probit functions do not detail the kind of structural damage suffered or limit state reached and are only available for broadly defined classes of components instead of those for specific equipment. Moreover, such dose-effect relationships are computed for a single incoming effect and do not account for superposition of different effects (i.e., overpressure and simultaneous thermal radiation) and/or superposition of the same effect generated from multiple sources. Both events can occur in the case of multiple simultaneous interacting chains of accidents likely to be generated following an earthquake. Finally, Probit curves are assumed for undamaged equipment, while all subsequent target units may have

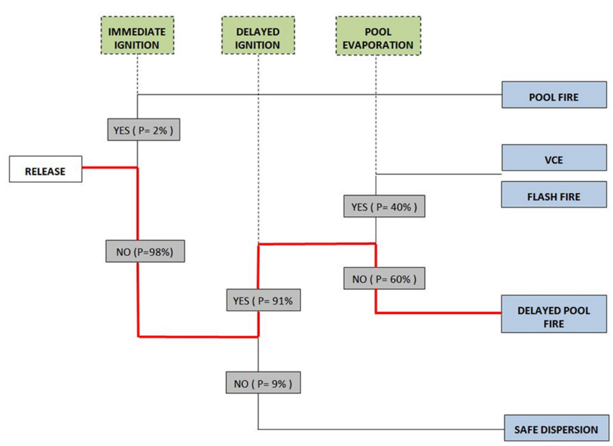

Fig. 18 One of the most probable accidental chains of a refinery tank farm obtained by Monte Carlo Simulations [101] (Reprinted with permission from Elsevier © 2018)

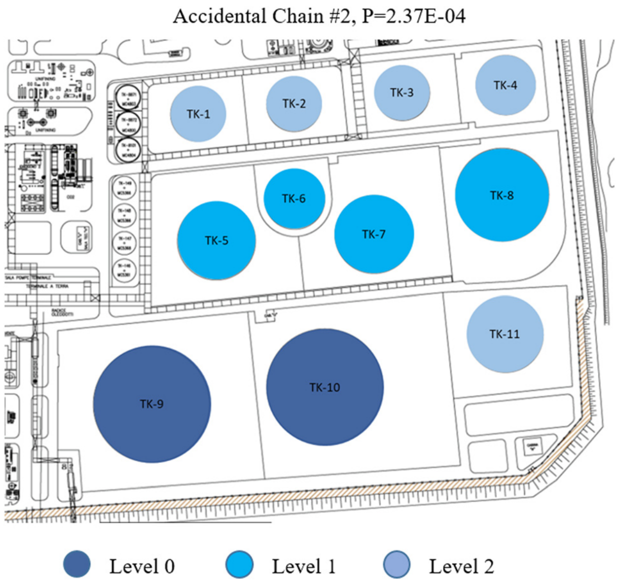

Fig. 19 Example of event tree for storage tanks [101] (Reprinted with permission from Elsevier © 2018)

been already partially damaged by the seismic excitation. The whole equipment failure probability can be estimated from the probabilities of failure according to each single effect [100], but the manner similar effects intensities are combined, as well as the vulnerability degradation caused by the earthquake, needs specific investigation. Therefore, seismic QRA in CPPs would much benefit from development of cumulative damage Probit curves deriving from superposition of seismic inputs and other physical effects.

As an additional issue, it should be remarked that Probit curves are available for major equipment only. This leads to neglect piping connections in the existing seismic QRA approaches. Owing to their elasticity and low mass, pipes are considered to be capable of surviving earthquakes. Nevertheless, the tank-piping system is a complex coupled system, as leakages can occur either at the tank-pipe connection flanges or along the pipe route. Moreover, pipe rupture may happen due to physical collapse of nearby equipment. Novel methods should be developed to model LOC events and pipe connections fragility according to their layout and the interaction with surrounding equipment. The effect of spatial variability of the seismic input on substructures and asynchronous motion and consequent constraints and differential displacement of supports needs to be investigated.

Pipes, may be, instead, more susceptible to velocity or displacement. Novel methods to compute fragility curves for piping systems should be then developed, based on the pipe layout and characteristics of the connected equipment. In fact, fragility curves developed for stand-alone equipment may not catch coupling effects of interconnected equipment, i.e., differential displacements on pipe joints. Nevertheless, if piping fragility estimation shall be incorporated in plant-wide seismic QRA, this has to be carried out without resorting to complex structural modeling, as carried out for instance in the existing literature [42,43,50], which is not compatible with the computational burden of a multiple scenario and multiple unit analysis; see, in this respect, Fig. 20. Finally, most seismic QRA methods assume that major equipment would be located at ground level. However, in process plants, equipment can also be installed in multilevel

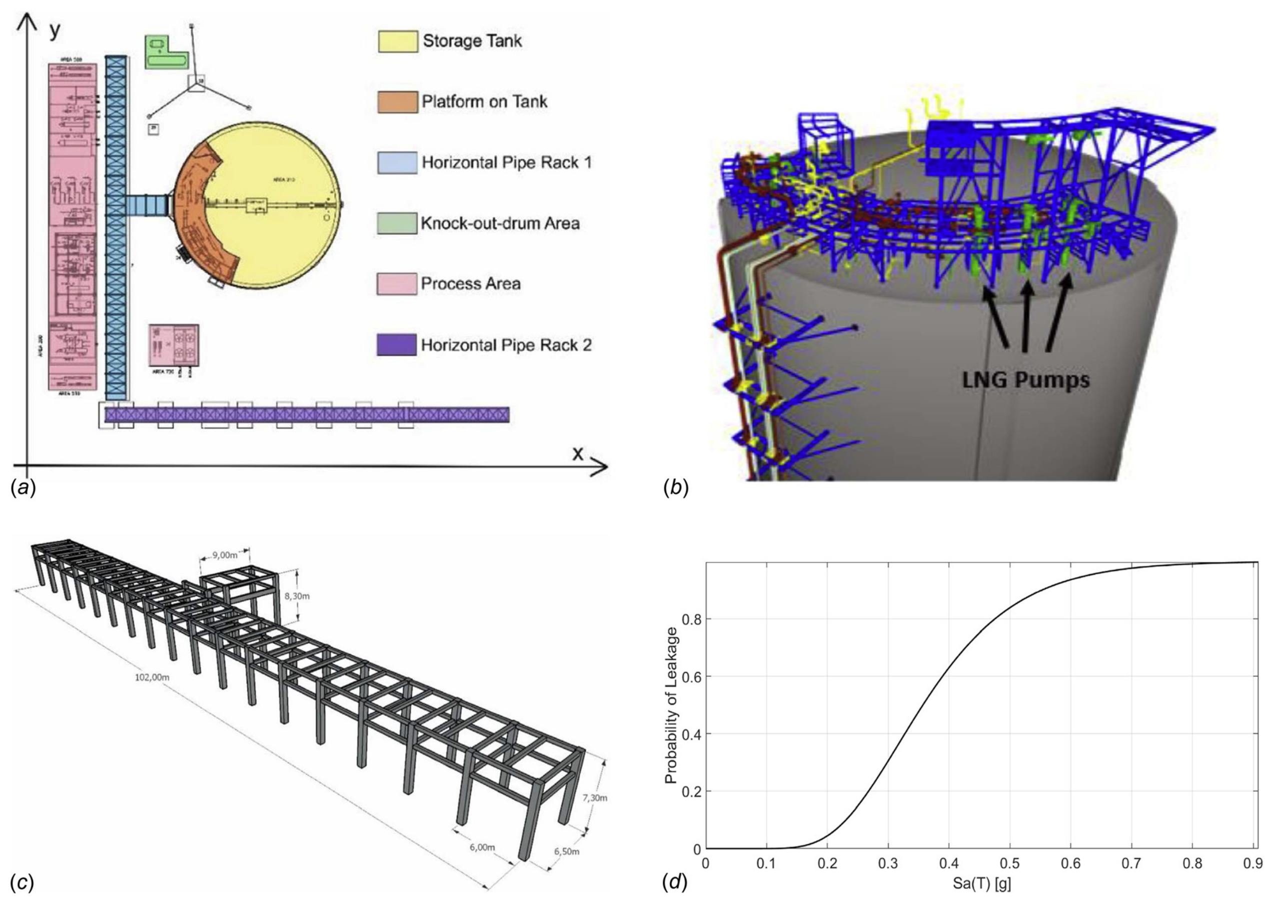

Fig. 20 Example of LNG plant analyzed in [42] (Reprinted with permission from Elsevier © 2018): (*a*) plant layout, (*b*) LNG tank, (*c*) pipe rack, and (*d*) seismic vulnerability of the plant in terms of leakage

Table 2 List of methods employed for seismic quantitative risk analysis

Authors	Year	Risk analysis	LOC/*D* relationship	Fragility curves	Domino effects	Multiple starting scenarios	Software
Keremidjian et al [122]	1985	Analytical	Deterministic	Empirical	No	No	—
Seligson et al. [123]	1996	Analytical	Deterministic	Empirical	Yes	Yes	—
Girgin and Krausmann [4]	2013	Analytical	Deterministic	Empirical	Yes	No	RAPID-N
Busini et al. [124]	2011	Analytical	Deterministic	Empirical	Yes	Yes	—
Salzano et al. [23]	2009	Analytical	Deterministic	Empirical	Possible	No	—
Antonioni et al. [17]	2007	Analytical	Deterministic	Empirical	Yes	No	ARIPAR-GIS
Cozzani et al. [20]	2014	Analytical	Deterministic	Empirical	Yes	Yes	—
Sadeg-Azar et al [126]	2014	Monte Carlo	Deterministic	Empirical	No	No	—
Caputo and Vigna [127]	2017	Analytical	Deterministic	Analytical	Yes	Yes	Proprietary MATLAB code
Alessandri et al [101]	2018	Monte Carlo	Deterministic	Analytical	Yes	Yes	PRIAMUS

structures [118]. Then, complex coupling between equipment, supporting structure, and connecting piping occurs. This can induce additional difficulties in evaluating the effects of damage propagation.

8 Seismic Quantitative Risk Assessment Methodologies for Process Plants

A seismic QRA methodology, including in a detailed and realistic manner all steps listed in Sec. 3, is not yet available, despite more than a decade of research effort. In fact, while in the past literature about seismic risk assessment in CPPs was scarce, as compared to other civil and industrial sectors, in recent times an increased attention toward this issue is witnessed by funding of dedicated international research projects, such as LESSLOSS [119], STREST [120], INDUSE [25], INDUSE-2-SAFETY [96], and XP-Resilience [121], as well as by the appearance in the academic literature of specific seismic QRA approaches for CPPs.

Kiremidjian et al. [122] were among the first to develop a comprehensive risk assessment model for major process plants. They adopted a structural reliability-based approach focusing on the degradation of plant functionality following an earthquake, but neglected propagation phenomena and the multiplicity of starting scenarios. Seligson et al. [123] fused on assessing consequences of earthquake-caused release of toxic chemicals over a large land area in California, including multiple facilities, but relied on simplified process models of each chemical plant. Girgin and Krausmann [4] developed the RAPID-N software tool which allows for a unified and rapid screening of Na-Tech hazards including earthquakes. This tool is able to display the impact zone of material release but neglects damage propagation effects. With the same goal, Busini et al. [124] proposed a simplified short-cut screening procedure for NaTech risks based on the computation of some key hazard indicators useful to summarize the NaTech risk level associated with a given earthquake scenario, e.g., a plant located in a given position. This allows for a rapid ranking of the most dangerous plants or subplants before performing a more detailed QRA. The procedure was then extended to assess the vulnerability of a surrounding territory by Marzo et al. [125].

More detailed seismic QRA methods were at first developed to analyze single equipment types, in particular oil storage tanks and tanks farms. Salzano et al. [39] focused on determining fragility curves for atmospheric storage tanks and subsequently extended the method to consequence estimation and damage propagation [98], while inclusion of early warning systems was suggested by Salzano et al. [23].

However, the first approaches used to formalize a generalizable procedure including in a systematic manner distinct equipment categories and scenario analysis according to the above-listed steps were proposed by Antonioni et al. [17] and Campedel et al. [18], and further refined by Cozzani et al. [20]. In such works, accident scenarios are based on a combination of equipment independently damaged by the earthquake, and propagation effects are included, although limited to second level scenarios only. Moreover, LOC estimation was based on a deterministic association with predetermined equipment damage states following what indicated in Refs. [39] and [98]. More recently, Sadeg-Azar et al. [126] developed a method for probabilistic seismic analysis of industrial facilities based on fragility curves and Monte Carlo sampling, but focusing on structural response of single equipment only and neglecting escalation phenomena.

A further attempt to better integrate systematic scenario analysis and uncertainty propagation within a general framework has been made in Refs. [100] and [127]. Therein, all starting damage scenarios and resulting chains of accidents are analyzed, until propagation effects stop. Specific chains of accidents are not individually dealt with, but rather the overall set of possible multiple and interacting chains of accidents triggered by each starting scenario is simultaneously considered and the resulting expected loss distribution is computed. As an alternative, Monte Carlo simulation has also been used to generate sample chains of accidents starting from seismic equipment damage through random LOC generation and effects propagation [21] and [101]. Several proposed methods are summarized in Table 2 along with the main characteristics.

Apart from the general methods summarized earlier, a few case study analyses are also available; in particular, some referred to oil storage plants [128,129], while in Ref. [130] the authors focused on analyzing fires following an earthquake in petrochemical enterprises. Some case studies also carried out a detailed analysis of subplants explicitly including piping connections [42].

Overall, from the earlier discussion results that although generalizable and comprehensive seismic QRA frameworks specific for CPPs have been made available in the last decade, the underlying implementation procedures are somewhat simplified, and some relevant issues still need to be investigated in depth.

9 Perspectives and Future Research

In practical seismic risk assessment, the uncertainty is commonly treated by probabilistic methods, relying on Bayesian formulation [131], for the treatment of rare events and poorly known processes typical of high-consequence technologies. However, purely probability-based approaches to risk and uncertainty analysis are characterized by conditions of limited or poor knowledge on the high consequence risk problem for which the information available does not provide a strong basis for a specific probability estimation. Moreover, it becomes subjective when Bayesian approaches are adopted [132]. As a result, other frameworks are available where all the uncertainties are kept plain with no additional information inserted in the analytic evaluation in the form of assumptions which cannot be proven. We mention among them the imprecise probability, after [133], and the random sets in the two forms proposed in Refs. [134] and [135]. These frameworks should be explored in process plants.

Another limitation of the classical seismic QRA framework is the binary logic and deterministic cause-effect constructs that are at the core of inductive/deductive fault tree-event tree techniques that limit the spectrum of real world risk causal factors. As a result, hybrid methods that tend to mix fundamentally different representational and computation techniques, e.g., Monte Carlo randomization of deterministic logic or introduction of event sequence diagram—to model temporal sequences of events at a relatively high level of abstraction—should be included in risk scenarios. See, for instance, Ref. [136], with respect to logic-based simulation.

With regard to PSHA, for which several issues have been discussed in Sec. 4, full probabilistic approaches are now available for incorporating site effects and the wide range of frequencies typical of impulsive and convective motions in tanks [137]. Also, vertical components of the motion can be taken into account [138]. The challenge here is to develop seismic hazard models able to get rid of attenuation relationships.

As mentioned in the Introduction section, seismic QRA of process facilities relies on approximate fragility curves and Probit functions of units, which were largely evaluated in the sixties and, therefore, are not suitable for more recent equipment. As a result, a large research effort is needed for critical components of plants in this area. This also includes the proper definition of LOC of critical components like tanks, pipe elbows, bolted flanges, and Tee joints.

It is evident that CCPs need to be thought as part of the network of infrastructures, characterized by high consequence risk complex systems with limited knowledge behavior. As such, resilience analyses need to carried out. Along the line of the paper of Caputo and Paolacci [139,140], additional studies to quantify the resilience of process plants and nearby communities need to be carried out.

Needless to say that in order to accurately characterize structure integrity and dynamic properties of substructure parts of piping systems, elbows, etc., other techniques like nondestructive evaluation—for instance, passive acoustic emission for crack detection and localization, local wall thinning of elbows—and structural health monitoring can be adopted. They can be very useful to carry out the additional validation compatible with the formats of API Standard 579-1 [141]. This step can naturally lend to an additional level, which allows for decision/repair procedures tailored to meet the specific needs of the situation. These tailored repair solutions are safe and cost-effective in lieu of the one-size fits all cut-out methods of decision and repair.

10 Conclusions

Some of the strengths and limitations of seismic quantitative risk assessment methodologies as used in some technological sectors, primarily chemical process plants have been discussed. More precisely, different sections of the paper presented different facets of seismic QRA of CPPs and a number of methodological improvements that can significantly enhance the quality of seismic QRA have also been listed. De facto, current methods remain adequate only for certain type of facilities, like LNG plants, where domino effects are not present. Conversely, for more complex process plants, the next generation of QRA methods and tools are likely to be based on more complex analysis tools. Their main characteristics are (a) the development of QRA frameworks where all the uncertainties are kept plain with no additional information inserted in the analytic evaluation in the form of assumptions which cannot be proven; (b) the employment of hybrid methods in risk scenarios that tend to mix fundamentally different representational and computation techniques, e.g., Monte Carlo randomization of deterministic logic or introduction of event sequence diagram—to model temporal sequences of events at a relatively high level of abstraction; (c) the development of probabilistic seismic hazard analysis that does not rely on attenuation relationships; (d) the setting of fragility curves and Probit functions of units relevant to recent equipment; (e) the proper definition of loss of containment of critical components like tanks, pipe elbows, bolted flanges, and Tee joints; (f) the need for additional studies focused on the quantification of the resilience of CCPs and nearby communities; and (g) the adoption of nondestructive evaluation and structural health monitoring technique capable of enhancing the formats of API Standard 579-1 [141] to allow for decision/repair procedures tailored to meet the specific needs of the situation.

All in all, the aforementioned suggested area of research should improve the reliability, sustain the safety, reduce downtime costs, and extend the life of process plants and, in general, of energy production and storage facilities. Their coherent integration should entail a more effective decision making.

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Nomenclature

CMS = conditional mean spectrum
CPP = chemical process plant
DS = damage state
EDP = engineering demand parameter
GMPE = ground motion predictive equation
ICHEME = Institution of Chemical Engineers
IM = intensity measure
LOC = loss of containment
LS = limit state
Na-Tech = natural technological
NPP = nuclear power plant
QRA = quantitative risk analysis
UHS = uniform hazard spectrum

References

[1] Krausmann, E., Cozzani, V., Salzano, E., and Renni, E., 2011, "Industrial Accidents Triggered by Natural Hazards: An Emerging Risk Issue," Nat. Hazard Earth Sys., **11**(3), pp. 921–929.
[2] Campedel, M., 2008, "Analysis of Major Industrial Accidents Triggered by Natural Events Reported in the Principal Available Chemical Accident Databases," Institute for the Protection and Security of the Citizen, Ispra, Italy, Report No. EUR 23391 EN.
[3] European Parliament, 2012, "Directive 2012/18/EU (Seveso III) on the Control of Major-Accident Hazards Involving Dangerous Substances Amending and Subsequently Repealing Council Directive 96/82/EC," European Union, Bruxelles, pp. 1–37.
[4] Girgin, S., and Krausmann, E., 2013, "RAPID-N: Rapid Natech Risk Assessment and Mapping Framework," J. Loss Prev. Process, **26**(6), pp. 949–960.
[5] HAZUS, 2001, *Earthquake Loss Estimation Methodology*, National Institute of Building Science, Risk Management Solutions, Menlo Park, CA.
[6] Hinz, G., and Kerkhof, K., 2013, "System Identification and Reduction of Vibrations of Piping in Different Conditions," ASME Paper No. PVP2013-97694.
[7] McDaniels, T., Chang, S., Cole, D., Mikawoz, J., and Longstaff, H., 2008, "Fostering Resilience to Extreme Events Within Infrastructure Systems: Characterizing Decision Contexts for Mitigation and Adaptation," Global Environ. Change, **18**(2), pp. 310–318.
[8] Choun, Y. S., and Elnashai, A. S., 2010, "A Simplified Framework for Probabilistic Earthquake Loss Estimation," Probab. Eng. Mech., **25**(4), pp. 355–364.
[9] Huang, Y. N., Whittaker, A. S., and Luco, N., 2011, "A Probabilistic Risk Assessment Procedure for Nuclear Power Plants—Part I: Methodology," Nucl. Eng. Des., **241**(9), pp. 3996–4003.
[10] Huang, Y. N., Whittaker, A. S., and Luco, N., 2011, "A Probabilistic Seismic Risk Assessment Procedure for Nuclear Power Plants—Part II: Application," Nucl. Eng. Des., **241**(9), pp. 3985–3995.
[11] Kim, J. H., Choi, I. K., and Park, J. H., 2011, "Uncertainty Analysis of System Fragility for Seismic Safety Evaluation of NPP," Nucl. Eng. Des., **241**(7), pp. 2570–2579.
[12] Young, S., Balluz, L., and Malilay, J., 2004, "Natural and Technologic Hazardous Material Releases During and After Natural Disasters: A Review," Sci. Total Environ., **322**(1–3), pp. 3–20.
[13] Kim, H., Heo, G., and Jung, S., 2016, "QRA considering Multi-Vessel Failure Scenarios Due to a Natural Disaster—Lessons From Fukushima," J. Loss Prev. Process Ind., **44**, pp. 699–705.

[14] TNO, 1992, "Methods for the Determination of Possible Damage, Green Book," Director General of Labour, Voorburg, The Netherlands, Report No. CPR16E.
[15] Cozzani, V., and Salzano, E., 2004, "Threshold Values for Domino Effects Caused by Blast Wave Interaction With Process Equipment," J. Loss Prev. Process Ind., **17**(6), pp. 437–447.
[16] Mingguang, Z., and Juncheng, J., 2008, "An Improved Probit Method for Assessment of Domino Effect to Chemical Process Equipment Caused by Overpressure," J. Hazard. Mater., **158**(2–3), pp. 280–286.
[17] Antonioni, G., Spadoni, G., and Cozzani, V., 2007, "A Methodology for the Quantitative Risk Assessment of Major Accidents Triggered by Seismic Events," J. Hazard. Mater., **147**(1–2), pp. 48–59.
[18] Campedel, M., Cozzani, V., Garcia-Aneda, A., and Salzano, E., 2008, "Extending the Quantitative Assessment of Industrial Risks to Earthquake Effects," Risk Anal., **28**(5), pp. 1231–1246.
[19] Caputo, A. C., Giannini, R., and Paolacci, F., 2015, "Quantitative Seismic Risk Assessment of Process Plants: State of the Art Review and Directions for Future Research," ASME Paper No. PVP2015-45374.
[20] Cozzani, V., Antonioni, G., Landucci, G., Tugnoli, A., Bonvicini, S., and Spadoni, G., 2014, "Quantitative Assessment of Domino and Natech Scenarios in Complex Industrial Areas," J. Loss Prev. Process Ind., **28**, pp. 10–22.
[21] Alessandri, S., Caputo, A. C., Corritore, D., Giannini, R., Paolacci, F., and Phan, H. N., 2017, "On the Use of Proper Fragility Models for Quantitative Seismic Risk Assessment of Process Plants in Seismic Prone Areas," ASME Paper No. PVP2017-65137.
[22] Paolacci, F., Giannini, R., and De Angelis, M., 2012, "Analysis of the Seismic Risk of Major-Hazard Industrial Plants and Applicability of Innovative Seismic Protection Systems," *Petrochemicals*, P. Vivek, ed., IntechOpen, London.
[23] Salzano, E., Agreda, A. G., Carluccio, A., and Fabbrocino, G., 2009, "Risk Assessment and Early Warning Systems for Industrial Facilities in Seismic Zones," Reliab. Eng. Syst. Saf., **94**(10), pp. 1577–1584.
[24] Paolacci, F., Giannini, R., and De Angelis, M., 2013, "Seismic Response Mitigation of Chemical Plant Components by Passive Control Systems," J. Loss Prev. Process Ind., **26**(5), pp. 879–948.
[25] Karamanos, S., Bursi, O. S., Reza, M. S., Paolacci, F., Varelis, G., and Hoffmeister, B., 2013, "Structural Safety of Industrial Steel Tanks, Pressure Vessels and Piping Systems Under Seismic Loading," INDUSE Project, Research Fund for Coal and Steel, European Union, Luxembourg, Final Report No. RFSR-CT-2009-00022.
[26] Ballantyne, D., O'Rourke, G., Krinitzsky, M., and Ellis, L., 1991, "Lifelines: Costa Rica Earthquake, April 22, 1991," Earthquake Spectra, **7**(S2), pp. 93–117.
[27] Stepp, J. C., Swan, S., Wesselink, L., Haupt, R. W., Larder, R. R., Bachman, R. E., Malik, L., Eli, M., and Porush, A., 1990, "Industrial Facilities," Earthquake Spectra, **6**(S1), pp. 189–238.
[28] Kikic, S., Moncraz, P., and Noakowsky, P., 2001, "A Preliminary Analysis of the Tupras Refinery Stack Collapse During Kocaeli Earthquake of 17 August 1999," CICIND, Zurich, Switzerland, Vol. 17(1), CICIND Report.
[29] Di Carluccio, A., Fabbrocino, G., Salzano, E., and Manfredi, G., 2008, "Analysis of Pressurized Horizontal Vessels Under Seismic Excitation," 14th World Conference on Earthquake Engineering (WCEE), Beijing, China Oct. 12–17.
[30] Reza, M. S., Bursi, O. S., Paolacci, F., and Kumar, A., 2014, "Performance of Non-Standard Bolted Flange Joints in Industrial Piping Systems Subjected to Seismic Loading," J. Loss Prev. Process Ind., **30**, pp. 124–136.
[31] Thermal and Nuclear Power Engineering Society, 2011, "Special Topic: Reconstruction From the Earthquake (2nd report), Report of the Disaster Situation—Sendai Thermal Power Station and Shin-Sendai Thermal Power Station of Tohoku Electoric Power, Nakoso Power Plant of Joban Joint Power," Vol. 62, Thermal and Nuclear Power Engineering Society, Sendai, Japan, pp. 1–7 (in Japanese).
[32] Jain, S. K., Lettis, W. R., Murty, C. V. R., and Bardet, J. P., 2002, "Bhuj, India Earthquake Reconnaissance Report. Supplement to Earthquake Spectra," Vol. 18(S1), Earthquake Engineering Research Institute, Oakland, CA.
[33] Maekawa, A., 2012, *Recent Advances in Seismic Response Analysis of Cylindrical Liquid Storage Tanks, Earthquake-Resistant Structures*, M. Abbas, ed., IntechOpen, London.
[34] Mikami, A., Sato, Y., Otani, A., Iwamoto, K., and Iijima, T., 2009, "The Ultimate Strength of Cylindrical Liquid Storage Tanks Under Earthquakes, Elasto-Plastic Dynamic Analysis With FSI of Buckling Failure Modes," ASME Paper No. PVP2009-77067.
[35] Cortes, G., and Nussbaumer, A., 2011, "Experimental Study on the Seismic Behavior of Shell-Base Connections in Large Storage Tanks," Third International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN), Corfu, Greece, May 25–28, pp. 1–8.
[36] Matsui, T., 2009, "Sloshing in a Cylindrical Liquid Storage Tank With a Single-Deck Type Floating Roof Under Seismic Excitation," ASME J. Pressure Vessel Technol., **131**(2), p. 021303.
[37] Matsui, T., and Nagaya, T., 2012, "Nonlinear Sloshing in a Floating-Roofed Oil Storage Tank Under Long-Period Seismic Ground Motion," Earthquake Eng. Struct. Dyn., **42**(7), pp. 973–991.
[38] 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., **12**(2), pp. 255–263.
[39] Salzano, E., Iervolino, I., and Fabbrocino, G., 2003, "Seismic Risk of Atmospheric Storage Tanks in the Framework of Quantitative Risk Analysis," J. Loss Prev. Process Ind., **16**(5), pp. 403–409.
[40] Nishi, H., 2012, "Damage on Hazardous Materials Facilities," International Symposium on Engineering Lessons Learned From the 2011 Great East Japan Earthquake," Tokyo, Japan, Mar. 1–4, pp. 1–12.
[41] Scawthorn, C., and Johnson, G. S., 2000, "Preliminary Report: Kocaeli (Izmit) Earthquake of 17 August 1999," Eng. Struct., **22**(7), pp. 727–745.
[42] Bursi, O. S., Di Filippo, R., La Salandra, V., Pedot, M., and Reza, M. S., 2017, "Probabilistic Seismic Analysis of an LNG Subplant," J. Loss Prev. Process Ind., **53**, pp. 45–60.
[43] Bursi, O. E., Paolacci, F., Reza, M. S., Alessandri, S., and Tondini, N., 2016, "Seismic Assessment of Petrochemical Piping Systems Using a Performance-Based Approach," ASME J. Pressure Vessel Technol., **138**(3), p. 031801.
[44] Moat, A. M., Morrison, J. T. A., and Wong, S., 2000, "Performance of Industrial Facilities During 1999 Earthquakes: Implications for Risk Managers," Global Change and Catastrophe Risk Management: Earthquake Risks in Europe, EuroConference, Laxenburg, Austria, July 6–9, pp. 1–12.
[45] Kazama, M., and Noda, T., 2012, "Damage Statistics (Summary of the 2011 off the Pacific Coast of Tohoku Earthquake damage)," Soils and Foundations, **52**(5), pp. 780–792.
[46] Dobashi, R., 2014, "Fire and Explosion Disasters Occurred Due to the Great East Japan Earthquake (March 11, 2011)," J. Loss Prev. Process Ind., **31**, pp. 121–126.
[47] NFPA 59A, 2013, *Standards for the Production, Storage and Handling of Liquefied Natural Gas (LNG)*, National Fire Protection Association, Quincy, MA.
[48] Nuclear Energy Agency, 2008, "Differences in Approach Between Nuclear and Conventional Seismic Standards With Regard to Hazard Definition," CSNI Integrity and Ageing Working Group, Nuclear Energy Agency Committee on the Safety of Nuclear Installations, Organisation for Economic Co-operation and Development, Paris, France, Report No. NEA/CSNI/R(2007)17.
[49] BS EN, 2005, "Eurocode 8: Design of Structures for Earthquake Resistance–Part 1: General Rules, Seismic Actions and Rules for Buildings," British Standard EN, Brussels, Belgium, Standard No. EN 1998-1.
[50] Bursi, O. S., Reza, S. M., Abbiati, G., and Paolacci, F., 2015, "Performance-Based Earthquake Evaluation of a Full-Scale Petrochemical Piping System," J. Loss Prev. Process Ind., **33**, pp. 10–22.
[51] Cornell, A. C., 1968, "Engineering Seismic Risk Analysis," Bull. Seismol. Soc. Am., **58**(5), pp. 1583–1606.
[52] McGuire, R. K., 1995, "Probabilistic Seismic Hazard Analysis and Design Earthquakes: Closing the Loop," Bull. Seismol. Soc. Am., **85**(5), pp. 1275–1284.
[53] Sousa, L., Marques, M., Silva, V., and Varum, U., 2017, "Hazard Disaggregation and Record Selection for Fragility Analysis and Earthquake Loss Estimation," Earthquake Spectra, **33**(2), pp. 529–549.
[54] Bazzurro, P., and Cornell, C. A., 1999, "Disaggregation of Seismic Hazard," Bull. Seismol. Soc. Am., **89**(2), pp. 501–520.
[55] Rodriguez-Marek, A., Rathje, E. M., Bommer, J. J., Scherbaum, F., and Stafford, P. J., 2014, "Application of Single-Station Sigma and Site-Response Characterization in a Probabilistic Seismic-Hazard Analysis for a New Nuclear Site," Bull. Seismol. Soc. Am., **104**(4), pp. 1601–1619.
[56] Atkinson, G. M., 2006, "Single-Station Sigma," Bull. Seismol. Soc. Am., **96**(2), pp. 446–455.
[57] Choi, Y., and Stewart, J. P., 2005, "Nonlinear Site Amplification as Function of 30 m Shear Wave Velocity," Earthquake Spectra, **21**(1), pp. 1–30.
[58] Katsanos, E. I., Sextos, A. G., and Manolis, G. D., 2010, "Selection of Earthquake Ground Motion Records: A State-of-the-Art Review From a Structural Engineering Perspective," Soil Dyn. Earthquake Eng., **30**(4), pp. 157–169.
[59] Phan, H., Paolacci, F., and Alessandri, S., 2018, "Enhanced Seismic Fragility Analysis of Unanchored Steel Storage Tanks Accounting for Uncertain Modeling Parameters," ASME. J. Pressure Vessel Technol. (accepted).
[60] Baker, J. W., and Allin Cornell, C., 2005, "A Vector-Valued Ground Motion Intensity Measure Consisting of Spectral Acceleration and Epsilon," Earthquake Eng. Struct. Dyn., **34**(10), pp. 1193–1217.
[61] Abrahamson, N. A., 1992, "Non-Stationary Spectral Matching," Seismol. Res. Lett., **63**(1), p. 30.
[62] Mukherjee, S., and Gupta, V., 2002, "Wavelet-Based Generation of Spectrum-Compatible Time Histories," Soil Dyn. Earthquake Eng., **22**(9–12), pp. 799–804.
[63] Shome, N., Cornell, C. A., Bazzurro, P., and Carballo, J. E., 1998, "Earthquakes, Records, and Nonlinear Responses," Earthquake Spectra, **14**(3), pp. 469–500.
[64] Cimellaro, G. P., and Sebastiano, M., 2015, "A Computer-Based Environment for Processing and Selection of Seismic Ground Motion Records: OPENSIGNAL," Front. Built Environ., **1**, pp. 17–34.
[65] Baker, J. W., and Allin Cornell, C., 2006, "Spectral Shape, Epsilon and Record Selection," Earthquake Eng. Struct. Dyn., **35**(9), pp. 1077–1095.
[66] Baker, J. W., 2011, "Conditional Mean Spectrum: Tool for Ground-Motion Selection," J. Struct. Eng., **137**(3), pp. 322–331.
[67] Lin, T., Haselton, C. B., and Baker, J. W., 2013, "Conditional Spectrum-Based Ground Motion Selection—Part I: Hazard Consistency for Risk-Based Assessments," Earthquake Eng. Struct. Dyn., **42**(12), pp. 1847–1865.
[68] Lin, T., Haselton, C. B., and Baker, J. W., 2013, "Conditional Spectrum-Based Ground Motion Selection—Part II: Intensity-Based Assessments and Evaluation of Alternative Target Spectra," Earthquake Eng. Struct. Dyn., **42**(12), pp. 1867–1884.
[69] Baker, J. W., 2007, "Probabilistic Structural Response Assessment Using Vector-Valued Intensity Measures," Earthquake Eng. Struct. Dyn., **36**(13), pp. 1861–1883.

[70] Bazzurro, P., and Cornell, C. A., 2002, "Vector-Valued Probabilistic Seismic Hazard Analysis (VPSHA)," Seventh U.S. National Conference on Earthquake Engineering, Boston, MA, July 21–25, pp. 1–11.
[71] Housner, G. W., 1963, "The Dynamic Behavior of Water Tanks," Bull. Seismol. Soc. Am., **53**(2), pp. 381–387.
[72] Paolacci, F., Phan, H. N., Corritore, D., Alessandri, S., Bursi, O. S., and Reza, M. S., 2015, "Seismic Fragility Analysis of Steel Storage Tanks," Fifth ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Corfu, Greece, May 25–27, pp. 2054–2065.
[73] Malhotra, P. K., and Veletsos, A. S., 1994, "Uplifting Response of Unanchored Liquid-Storage Tanks," J. Struct. Eng., **120**(12), pp. 3524–3546.
[74] Phan, H. N., Paolacci, F., and P. Alessandri, S., 2016, "Fragility Analysis Methods for Steel Storage Tanks in Seismic Prone Areas," ASME Paper No. PVP2016-63102.
[75] Vathi, M., and Karamanos, S. A., 2018, "A Simple and Efficient Model for Seismic Response and Low-Cycle Fatigue Assessment of Uplifting Liquid Storage Tanks," J. Loss Prev. Process Ind., **53**, pp. 29–44.
[76] Phan, H. N., Paolacci, F., and Mongabure, F., 2017, "Nonlinear Finite Element Analysis of Unanchored Steel Liquid Storage Tanks Subjected to Seismic Loadings," ASME Paper No. PVP2017-65814.
[77] DeGrassi, G., Nie, J., and Hofmayer, C., 2008, "Seismic Analysis of Large Scale Piping Systems for the JNES-NUPEC Ultimate Strength Piping Test Program," U.S. Nuclear Regulatory Commission, Washington, DC, Report No. NUREG/CR-6983.
[78] Zeng, L., Jansson, L. G., and Venev, Y., 2014, "On Pipe Elbow Elements in ABAQUS and Benchmark Tests," ASME Paper No. PVP2014-28920.
[79] Otani, A., Shibutani, T., Morishita, M., Nakamura, I., and Shiratori, M., 2017, "Seismic Qualification of Piping System by Detailed Inelastic Response Analysis—Part 2: A Guideline for Piping Seismic Inelastic Response Analysis," ASME Paper No. PVP2017-65190.
[80] Azizpour, O., and Hosseisni, M., 2009, "A Verification of ASCE Recommended Guidelines for Seismic Evaluation and Design of Combination Structures in Petrochemical Facilities," J. Appl. Sci., **9**(20), pp. 3609–3628.
[81] Paolacci, F., Reza, M. S., and Bursi, O. S., 2011, "Seismic Analysis and Component Design of Refinery Piping Systems," COMPDYN-III, ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Corfu, Greece, May 26–28, pp. 1–24.
[82] Sone, A., Yamauchi, T., and Masuda, A., 2014, "A Load Combination Method for Seismic Design of Multi-Degree-of-Freedom Piping Systems With Friction Characteristics and Multiple Support Systems," ASME Paper No. PVP2014-28132.
[83] Vathi, M., Karamanos, S. A., Kapogiannis, I. A., and Spiliopoulos, K. V., 2015, "Performance Criteria for Liquid Storage Tanks and Piping Systems Subjected to Seismic Loading," ASME Paper No. PVP2015-45700.
[84] Campedel, M., Antonioni, G., Cozzani, V., Buratti, N., Ferracuti, B., and Savoia, M., 2008, "Quantitative Risk Assessment of Accidents Induced by Seismic Events in Industrial Sites," *Chemical Engineering Transaction*, Vol. 13, MIlan, Italy.
[85] Berahman, F., and Behnamfar, F., 2007, "Seismic Fragility Curves for Un-Anchored on-Grade Steel Storage Tanks: Bayesian Approach," J. Earthquake Eng., **11**(2), pp. 166–192.
[86] ALA, 2002, "Seismic Design and Retrofit of Piping Systems," American Lifelines Alliance, Federal Emergency Management Agency, Washington, DC.
[87] Buratti, N., and Tavano, M., 2014, "Dynamic Buckling and Seismic Fragility of Anchored Steel Tanks by the Added Mass Method," Earthquake Eng. Struct. Dyn., **43**(1), pp. 1–21.
[88] Bakalis, K., Vamvatsikos, D., and Fragiadakis, M., 2015, "Seismic Fragility Assessment of Steel Liquid Storage Tanks," ASME Paper No. PVP2015-45370.
[89] Iervolino, I., Fabbrocino, G., and Manfredi, G., 2004, "Fragility of Standard Industrial Structures by a Response Surface Based Method," J. Earthquake Eng., **8**(6), pp. 927–945.
[90] Phan, H. N., Paolacci, F., Corritore, D., Akbas, B., Uckan, E., and Shen, J. J., 2016, "Seismic Vulnerability Mitigation of Liquified Gas Tanks Using Concave Sliding Bearings," Bull. Earthquake Eng., **14**(11), pp. 3283–3299.
[91] Bu, S. J., and Abhinav, G., 2015, "Seismic Fragility of Threaded Tee-Joint Connections in Piping System," Int. J. Pressure Vessels Piping, **132–133**, pp. 106–118.
[92] Ehsan, S. F., Bub, G. J., Hyong, S. C., and Nam, S. K., 2015, "Seismic Fragility Analysis of Seismically Isolated Nuclear Power Plants Piping System," Nucl. Eng. Des., **284**, pp. 264–279.
[93] Caprinozzi, S., Ahmed, M., Paolacci, F., Bursi, O. S., and La Salandra, V., 2017, "Univariate Fragility Models for Seismic Vulnerability Assessment of Refinery Piping Systems," ASME Paper No. PVP2017-65138.
[94] Phan, H. N., and Paolacci, F., 2016, "Efficient Intensity Measures for Probabilistic Seismic Response Analysis of Anchored Above-Ground Liquid Steel Storage Tanks," ASME Paper No. PVP2016-63103.
[95] Wieschollek, M., Hoffmeister, B., and Feldmann, M., 2013, "Experimental and Numerical Investigations on Nozzle Reinforcements," ASME Paper No. PVP2013-97430.
[96] INDUSE 2 SAFETY, 2013, "Component Fragility Evaluation and Seismic Safety Assessment of 'Special Risk' Petrochemical Plants Under Design Basis and Beyond Design Basis Accidents," RFCS, European Union, Luxembourg, accessed July 30, 2018, http://www.induse2safety. unitn.it/
[97] Vathi, M., and Karamanos, S. A., 2015, "Simplified Model for the Seismic Performance of Unanchored Liquid Storage Tanks," ASME Paper No. PVP2015-45695.
[98] Fabbrocino, G., Iervolino, I., Orlando, F., and Salzano, E., 2005, "Quantitative Risk Analysis of Oil Storage Facilities in Seismic Areas," J. Hazard. Mater., **123**(1–3), pp. 61–69.
[99] O'Rourke, M., and So, P., 2000, "Seismic Fragility Curves for on-Grade Steel Tanks," Earthquake Spectra, **16**(4), pp. 801–815.
[100] Caputo, A. C., 2016, "A Model for Probabilistic Seismic Risk Assessment of Process Plants," ASME Paper No. PVP2016-63280.
[101] Alessandri, S., Caputo, A. C., Corritore, D., Giannini, R., Paolacci, F., and Phan, H. N., 2018, "Probabilistic Risk Analysis of Process Plants Under Seismic Loading Based on Monte Carlo Simulations," J. Loss Prev. Process Ind., **53**, pp. 136–148.
[102] Uijt De Haag, P. A. M., and Ale, B. J. M., 2005, "Guidelines for Quantitative Risk Assessment, Purple Book," Committee for the Prevention of Disasters, The Hague, Netherlands, Report No. CPR18E.
[103] Necci, A., Cozzani, V., Spadoni, G., and Khan, F., 2015, "Assessment of Domino Effect: State of the Art and Research Needs," Reliab. Eng. Syst. Saf., **143**, pp. 3–18.
[104] Kadri, F., and Chatelet, E., 2013, "Domino Effect Analysis and Assessment of Industrial Sites: A Review of Methodologies and Software Tools," Int. J. Comput. Distrib. Syst., **2**(III), pp. 1–10.
[105] Reniers, G., and Cozzani, V., 2013, *Domino Effects in the Process Industries*, Elsevier, Amsterdam, The Netherlands, p. 84.
[106] Salzano, S., and Cozzani, V., 2005, "The Analysis of Domino Accidents Triggered by Vapor Cloud Explosions," Reliab. Eng. Syst. Saf., **90**, pp. 271–284.
[107] Cozzani, V., Gubinelli, G., and Salzano, E., 2006, "Escalation Thresholds in the Assessment of Domino Accidental Events," J. Hazard. Mater., **129**(1–3), pp. 1–21.
[108] Cozzani, V., Tugnoli, A., and Salzano, E., 2007, "Prevention of Domino Effect. From Active and Passive Strategies to Inherently Safer Design," J. Hazard. Mater., **139**(2), pp. 209–219.
[109] Cozzani, V., Tugnoli, A., and Salzano, E., 2009, "The Development of an Inherent Safety Approach to the Prevention of Domino Accidents," Accid. Anal. Prev., **41**(6), pp. 1216–1227.
[110] Bernechea, E. J., Vilchez, J. A., and Arnaldos, J., 2013, "A Model for Estimating the Impact of the Domino Effect on Accident Frequencies in Quantitative Risk Assessments of Storage Facilities," Process Saf. Environ. Prot., **91**(6), pp. 423–437.
[111] Khan, F., and Abbasi, S. A., 1998, "DOMIFFECT: User Friendly Software for Domino Effect Analysis," Environ. Modell. Software, **13**(2), pp. 163–177.
[112] Abdolhamodzadeh, B., Abbasi, T., Rashtchian, D., and Abbasi, S. A., 2010, "A New Method for Assessing Domino Effect in Chemical Process Industry," J. Hazard. Mater., **182**(1–3), pp. 416–426.
[113] Khakzad, N., 2015, "Application of Dynamic Bayesian Network to Risk Analysis of Domino Effects in Chemical Infrastructures," Reliab. Eng. Syst. Saf., **138**, pp. 263–272.
[114] Khakzad, N., Khan, F., Amyotte, P., and Cozzani, V., 2013, "Domino Effect Analysis Using Bayesian Networks," Risk Anal., **33**(2), pp. 292–306.
[115] Khakzad, N., and Reniers, G., 2015, "Using Graph Theory to Analyze the Vulnerability of Process Plants in the Context of Cascading Effects," Reliab. Eng. Syst. Saf., **143**, pp. 63–73.
[116] Alileche, A., Olivier, D., Estel, L., and Cozzani, V., 2017, "Analysis of Domino Effect in the Process Industry Using the Event Tree Method," Saf. Sci., **97**, pp. 10–19.
[117] Vilchez, J. A., Espejo, V., and Casal, J., 2011, "Generic Event Trees and Probabilities for the Release of Different Types of Hazardous Materials," J. Loss Prev. Process Ind., **24**(3), pp. 281–287.
[118] Pinkawa, M., Hoffmeister, B., and Feldmann, M., 2014, "Floor Response Spectra Considering Influence of Higher Modes and Dissipative Behaviour," *Seismic Design of Industrial Facilities*, S. Klinkel, C. Butenweg, G. Lin, and B. Holtschoppen, eds., Springer Vieweg, Wiesbaden, Germany.
[119] LESSLOSS, 2004, "Risk Mitigation for Earthquakes and Landslides," European Union, Luxembourg, Report No. GOCE-CT-2003-505448.
[120] STREST, 2016, "Harmonized Approach to Stress Tests for Critical Infrastructures against Natural Hazards, STREST Reference Report: Report on Lessons Learned From Recent Catastrophic Events," G. Tsionis, A. Pinto, D. Giardini, and A. Mignan, eds., European Union, Luxembourg.
[121] XP-RESILIENCE, 2016, "Extreme Loading Analysis of Petrochemical Plants and Design of Metamaterial-Based Shields for Enhanced Resilience," European Union, Luxembourg, accessed July 30, 2018, http://r.unitn.it/en/dicam/xp-resilience
[122] Kiremidjian, A., Ortiz, K., Nielsen, R., and Safavi, B., 1985, "Seismic Risk to Major Industrial Facilities," Department of Civil and Environmental Engineering, Stanford University, Stanford, CA, Report No. 72.
[123] Seligson, H. A., Eguchi, R. T., Tierney, K. J., and Richmond, K., 1996, "Chemical Hazards, Mitigation and Preparedness in Areas of High Seismic Risk. A Methodology for Estimating the Risk of Post-Earthquake Hazardous Materials Release," National Centre for Earthquake Engineering Research, State University of New York, Buffalo, NY, Report No. NCEER-96-0013.
[124] Busini, V., Marzo, E., Callioni, A., and Rota, R., 2011, "Definition of a Short-Cut Methodology for Assessing Earthquake-Related Na-Tech Risk," J. Hazard. Mater., **192**(1), pp. 329–339.
[125] Marzo, E., Busini, V., and Rota, R., 2015, "Definition of a Short-Cut Methodology for Assessing the Vulnerability of a Territory in Natural-Technological Risk Estimation," Reliab. Eng. Syst. Saf., **134**, pp. 92–97.
[126] Sadeg-Azar, H., and Hasenbank-Kriegbaum, T. D., 2014, "Probabilistic Seismic Analysis of Existing Industrial Facilities," International Conference on

Seismic Design of Industrial Facilities (SeDIF), Aachen, Germany, Sept. 26–27, pp. 101–112.
[127] Caputo, A. C., and Vigna, A., 2017, "Numerical Simulation of Seismic Risk and Loss Propagation Effects in Process Plants: An Oil Refinery Case Study," ASME Paper No. PVP2017-65465.
[128] Romeo, R. W., 2014, "Seismic Risk Analysis of a Oil-Gas Storage Plant," Conference on Seismic Design of Industrial Facilities (SeDIF), Aachen, Germany, Sept. 26–27, ed., pp. 17–26.
[129] Korkmaz, K. A., Sari, A., and Carhoglu, A. I., 2011, "Seismic Risk Assessment of Storage Tanks in Turkish Industrial Facilities," J. Loss Prev. Process Ind., **24**(4), pp. 314–320.
[130] Li, J., Wang, Y., Chen, H., and Lin, L., 2014, "Risk Assessment Study of Fire Following an Earthquake: A Case Study of Petrochemical Enterprises in China," Nat. Hazards Earth Syst. Sci., **14**(4), pp. 891–900.
[131] Berger, J., 1994, "An Overview of Robust Bayesian Analysis," Test, **3**(1), pp. 5–124.
[132] Kwag, S., Oh, J., Lee, J. M., and Ryu, J.-S., 2017, "Bayesian-Based Seismic Margin Assessment Approach: Application to Research Reactor," Earthquakes Struct., **12**(6), pp. 653–663.
[133] Walley, P., 1991, *Statistical Reasoning With Imprecise Probabilities*, Chapman and Hall, New York.
[134] Dempster, A., 1967, "Upper and Lower Probabilities Induced by a Multivalued Mapping," Ann. Math. Stat., **38**(2), pp. 325–39.
[135] Shafer, G., 1976, *A Mathematical Theory of Evidence*, Princeton University Press, Princeton, NJ.
[136] Houtermans, M. J. M., Apostolakis, G. E., Brombacher, A. C., and Karydas, D. M., 2002, "The Dynamic Flowgraph Method—Ology as a Safety Analysis Tool: Programmable Electronic System Design and Verification," Saf. Sci., **40**(9), pp. 813–833.
[137] Haji-Soltani, A., and Pezeshk, S., 2017, "A Comparison of Different Approaches to Incorporate Site Effects in PSHA: A Case Study for a Liquefied Natural Gas Tank," Bull. Seismol. Soc. Am, **107**(6): pp. 2927–2947.
[138] Haji-Soltani, A., Pezeshk, S., Malekmohammadi, M., and Zandieh, A., 2017, "A Study of Vertical to Horizontal Ratio of Earthquake Components in the Gulf Coast Region," Bull. Seismol. Soc. Am., **107**(5), pp. 2055–2066.
[139] Caputo, A. C., and Paolacci, F., 2017, "A Method to Estimate Process Plant Seismic Resilience," ASME Paper No. PVP2017-65464.
[140] Dinh, L. T. T., Pasman, H., Gao, X., and Sam Mannan, M., 2012, "Resilience Engineering of Industrial Processes: Principles and Contributing Factors," J. Loss Prev. Process Ind., **25**(2), pp. 233–241.
[141] API/ASME, 2007, "Fitness for Service," The American Society of Mechanical Engineers, New York, Standard No. API 579-1/ASME FFS-1.