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Analysis of natech risk for pipelines: A review

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Roberta Piccinelli and Elisabeth Krausmann

Abstract

Natural events, such as earthquakes and floods, can trigger accidents in oil and gas pipeline with potentially severe consequences to the population and to the environment. These conjoint technological and natural disasters are termed natech accidents.

The present literature review focuses on the risk analysis state-of-the-art of seismic and flood events that can impact oil and gas transmission pipelines. The research has focused on methodologies that take into account the characteristics of natech events: for instance, the characterization of the triggering natural hazard and the final accident scenarios, as well as fragility curves for the specific assessment of the potential consequences of natech accidents.

The result of this research shows that the literature on seismic risk analysis offers the largest number of examples and methodologies, although most studies focused on structural damage aspects without considering the consequences of a potential loss of containment from the pipelines. Very little work was found on flood risk assessment of natech events in pipelines.

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1. Introduction

Risk analysis asks the questions: “What can go wrong? How likely is it to happen? What are the consequences?”

A first observation comes from the fact that there is risk if there is a potential source of danger, so the answer to the first question helps to identify the hazard or the potential adverse events and mechanisms by which the events may create undesired consequences, loss or damage. However, the presence of a hazard is not sufficient to define a condition of risk. Indeed, it is necessary to consider the uncertainty that the hazard translates from potential to actual damage: the likelihood of damage related to the hazard is expressed through probabilities (Kaplan and Garrick, 1981).

Natural events, e.g. floods, storms, volcanic eruptions, lightning, earthquakes or landslides, can lead to natural disasters. Recent years have seen a dramatic increase in the frequency and magnitude of natural catastrophes (Figure 1) due to climate change.

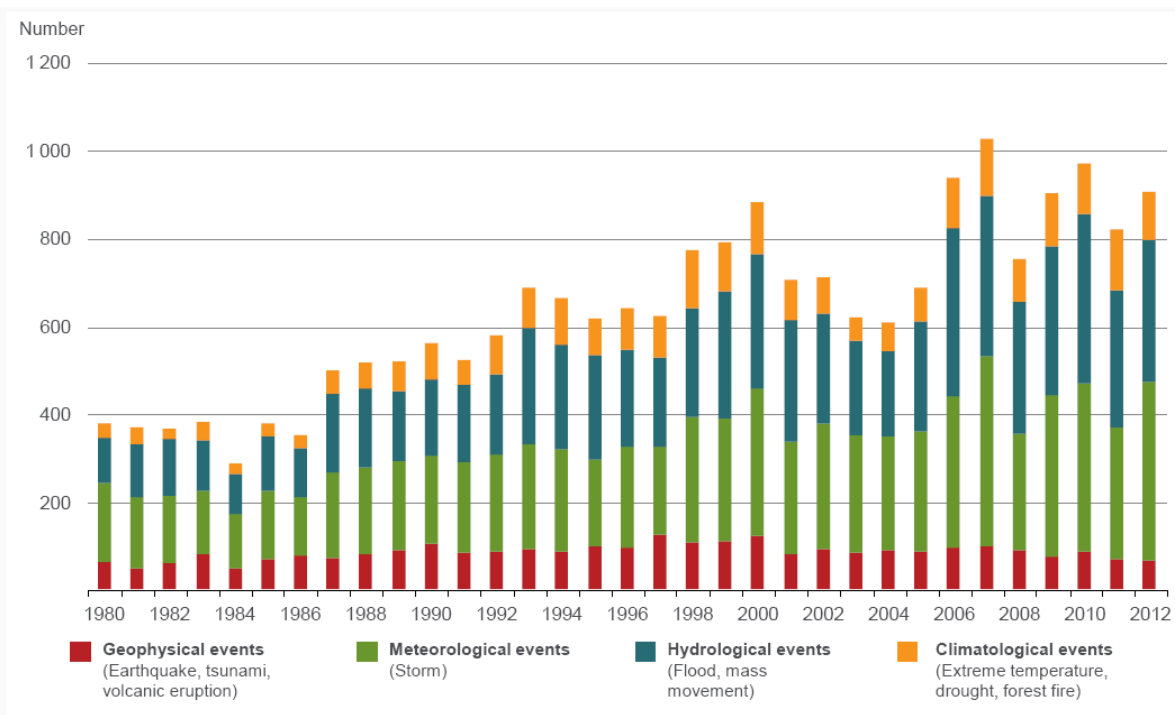


Figure 1. Graph of natural catastrophes worldwide 1980-2012. The number of events shows an increasing trend in frequency of “great” natural disaster (Munich RE, 2013)

The particularly high severity of some natural events is raising growing concern for the consequences of major accident scenarios that may be triggered by natural disasters. Natural calamities can cause severe disruptions in industrial facilities and critical infrastructures (e.g., process plants, chemical facilities, oil and gas pipelines) potentially triggering secondary disasters, such as toxic air releases, spills of

hazardous materials, fires or explosions (Young et al., 2004; Girgin, 2011; Krausmann et al., 2011 a,b). These conjoint natural and technological disasters are termed natech accidents.

Natural disasters and technological accidents have generally been studied as separate events; consequently, little information on their interaction was produced. Nevertheless, there is growing awareness of the risk posed by the simultaneous interaction of natural and technological hazards, and the need for developing integrated methodologies capable of estimating damage when different typologies of hazard are present (Krausmann et al., 2011b).

Studies of the natech accidents recorded in the major industrial–accident databases was performed to identify the most frequent natural disasters, the most vulnerable equipment categories, their failure mode and the resulting accident scenarios (Cozzani et al., 2010; Renni et al., 2010; Krausmann et al., 2011 a). Based on the operating conditions and the severity of potential accidental events associated, these studies called attention to pipeline natech accidents triggered by earthquakes and floods. Numerous severe accidents bear testimony to the risk associated with natural hazard impact on pipelines transporting dangerous substances. In the USA in 1994, flooding of the San Jacinto River led to the rupture of 8 and the undermining of 29 pipelines by the flood waters. Subsequently, 5.5 million litres of petroleum and related products were released into the river and ignited. Overall, 547 people were injured due to inhalation and burns (NTSB, 1996).

Although pipeline releases have caused relatively few fatalities in absolute numbers, a single pipeline accident could be catastrophic in terms of deaths and environmental damage. The possibly wide spatial extent of natural disasters such as earthquakes and floods may actually simultaneously affect several equipment items of distributed systems such pipelines. Moreover, emergency response may be delayed by the natural event.

Such accidents have generated persistent scrutiny of pipeline regulators and have increased national and community activity related to pipeline safety (Parfomak, 2013). Methodologies and tools, e.g. RAPID-N (2013), RAI² (2012) or ARIPAR (Campedel et al., 2008), for the specific assessment of the potential consequences of natech accidents are only recently under development but some specific scenarios and models that link the severity of the natural hazard to its impact on specific components are still missing (Krausmann et al., 2011 a).

When developing a specific natech approach for risk assessment, the standard risk management procedure that should be adhered to is summarized in Table I.

In this general framework, both the qualitative and the quantitative risk analysis need to take into account the characteristics of natech events: for instance, a dedicated approach to the characterization of the triggering natural hazard or disaster and the final accident scenarios.

From this (natech) standpoint, the present literature review focuses on the risk analysis state-of-the-art of seismic and flood events that can impact (oil and gas) transmission pipelines.

Table I. Technical steps in the risk management process (Mannan, 2005; CCPS, 2000)

Step	Activity
1	Planning the risk management process: this involves the definition of the level of detail and the tools to use in the analysis
2	Hazard identification: this comprises all the activities required to identify all hazards related to the examined system
3	Qualitative risk analysis: this involves screening activities aimed at identifying where and when more detailed analyses are required
4	Quantitative risk analysis: this involves quantifying both occurrence of probability and expected consequence magnitude of each identified hazard to estimate an overall risk index
5	Planning the mitigation measures: this requires the implementation of all the prevention and protection measures necessary to keep the risk level below the acceptable threshold
6	Risk monitoring and control: this comprises the activities required to avoid changes that would increase the risk level above the acceptable threshold

2. Seismic vulnerability of pipelines

The earthquake impact on pipelines may result in releases of hazardous materials and possibly major accidents leading to injuries and fatalities to people in the nearby area. In 1994, an oil spill of more than 3500 barrels occurred on the Santa Clara River as a result of a pipeline rupture during the Northridge (Colorado, USA) earthquake. Several releases occurred from this break which caused approximately 5 miles of pipeline to empty to the ground and into the river (Leville et al., 1995).

Most major oil and gas pipelines generally run underground: although they are less exposed to the inertial forces than the above-ground pipelines, the seismic response of pipelines is dominated by soil deformation, so that vulnerability assessment strongly depends on the ground – pipeline interaction.

In the following, a literature review of earthquake severity measures will be provided together with fragility curves, which give the probability of damage based on specific intensity parameters, or threshold values of the seismic intensity. Fragility curves are an essential component of pipeline risk analysis.

2.1 Earthquake severity measures

A main issue related to the seismic risk analysis of pipelines is the selection of an appropriate earthquake intensity measure (IM) that characterizes the strong ground motion and best correlates with

the response of each element. Several measures of the strength of ground motion have been developed. Each intensity measure may describe different characteristics of the motion, some of which may be more damaging for the structure or system under consideration. The use of a particular IM in seismic risk analysis should be guided by the extent to which the measure corresponds to damage to local elements of a system or the global system itself. Optimum intensity measures are defined in terms of practicality, effectiveness, efficiency, sufficiency, robustness and computability (Cornell et al, 2002; Mackie and Stojadinovich, 2003; 2005).

- Practicality refers to the recognition that the IM has some direct correlation to known engineering quantities and that it “makes engineering sense” (Mackie and Stojadinovich, 2005; Mehanny, 2009).
- Sufficiency describes the extent to which the IM is statistically independent of ground motion characteristics such as magnitude and distance (Padgett et al., 2008). A sufficient IM is one that renders the structural demand measure conditionally independent of the earthquake scenario.
- The effectiveness of an IM is determined by its ability to evaluate its relation with an engineering demand parameter (EDP) in closed form (Mackie and Stojadinovich, 2003), so that the mean annual frequency of a given decision variable exceeding a given limiting value (Mehanny, 2009) can be determined analytically.
- The most widely used quantitative measure from which an optimal IM can be obtained is efficiency. This refers to the total variability of an engineering demand parameter for a given IM (Mackie and Stojadinovich, 2003; 2005).
- Robustness describes the efficiency trends of an IM-EDP pair across different structures, and therefore different fundamental period ranges (Mackie and Stojadinovich, 2005; Mehenny, 2009).

In general, two main IM classes exist: empirical intensity measures and instrumental intensity measures. With regard to the empirical IMs, different macro-seismic intensity scales could be used to identify the observed effects of ground shaking over a limited area. With respect to instrumental IMs, the severity of ground shaking can be expressed as an analytical value measured by an instrument or computed through the analysis of recorded accelerograms.

The seismic response of underground structures is considerably different from that of above-ground facilities. While the latter ones act as a kind of inertial filter on the incident ground motion, the seismic response of buried structures is dominated by the surrounding soil deformation, and inertial soil-structure interaction effects are generally negligible (St. John and Zahrah, 1987). Therefore, one of the critical aspects behind the seismic design and assessment of underground structures is the proper definition of the input ground motion. The strain evaluation is important for the vulnerability, as well. A direct measure of the ground strain is not generally available, since strain networks are not generally equipped with strain-meters; therefore, simplified formulas relating peak ground strain to peak ground velocity are typically used.

The selection of the intensity parameter is also related to the approach that is followed for the derivation of fragility curves and the type of element at risk. For example, as the empirical curves relate the observed damage with the seismic intensity, the latter may be described based on the intensity of records of seismic motions, and thus peak ground acceleration (PGA) or peak ground velocity (PGV) may be suitable IMs. On the other hand, the spatial distribution of PGA values is easier to be estimated through simple or advanced methods within a seismic hazard study of a specific area (e.g., Esposito and Iervolino, 2011). When the vulnerability of elements due to ground failure is examined (i.e. liquefaction, fault rupture, landslides), permanent ground deformation (PGD) is the most appropriate IM. Seismic fragility curves relate pipeline damage rates to different levels of seismic intensity. In the literature, various ground motion parameters have been used to describe the seismic event. Here a brief description is presented.

Previously, seismic intensity has been measured by using the Modified Mercalli Intensity Scale (MMI) which is an empirical intensity measure. This scale is composed of 12 increasing levels of intensity that range from imperceptible shaking to catastrophic destruction: the lower numbers of the intensity scale generally deal with the manner in which the earthquake is felt by people; the higher numbers of the scale are based on observed structural damage. This scale does not have a mathematical basis; instead it is an arbitrary ranking based on observed effects. The obtained values depend on the characteristics of the existing structural system and natural environment (USGS, 2013). This is a limitation because the description is restricted to local characteristics and because it is not an objective scale. Nevertheless MMI maps are still used and many relations for the performances of structures during earthquakes are dependent on MMI. For example Santella et al. (2011) report a delineation of five seismic zones for earthquakes using the MMI zones based on Shakemaps, obtained from the US Geological Survey (USGS) Earthquake Center (USGS, 2013).

More recently, the improvement in measurement techniques has allowed the use of more objective seismic parameters (instrumental intensity measures). The most significant synthetic parameters are the PGA and PGV. PGA is the peak of the horizontal acceleration time history. Since PGA is directly related to the structure, because of its proportionality with inertial effects due to seismic loading, it is more appropriate for above-ground structures (Lanzano et al., 2013a). For underground structures, the damaging effects due to the passage of the seismic waves in the soil are proportional to PGV, which is the peak value of the horizontal velocity time histories.

These parameters are only a concise description of the information of the local motion of the soil: they are available only at the instrumented site. Predictive correlations (attenuation laws) are used to give a value of the parameters for an extended area (Douglas, 2004).

Based on the experience and data collected during past earthquakes, geotechnical dynamics effects related to pipeline damage can be divided in two categories (O'Rourke and Liu, 1999):

- Strong Ground shaking (SGS): the common effect is a deformation of the soil which surrounds the pipeline, without breaks or ruptures in the soil, depending on the earthquake intensity;

- Ground Failure (GF): the surrounding soil is affected by failure phenomena caused by the earthquake as active fault movement (GF1), liquefaction (GF2), and landslides induced by the shaking (GF3). These seismic failure mechanisms appear only under specific geotechnical conditions and are site dependent.

2.2 Description of pipelines

Pipelines are important structural components in industrial and civil facilities. They are used to transport and distribute liquid and gaseous materials such as oil and natural gas in energy assets, hazardous chemicals and gases such as ammonia and ethylene in process plants and water in urban areas. Most hazardous liquid and gas pipelines are buried underground, but there are several major above-ground structures, such as the Trans-Alaska Pipeline System.

Based on their function, pipelines can be classified as (Hopkins, 2002):

- Flow-lines and gathering lines: these short distance lines gather various products and move them towards processing facilities.
- Feeder lines: these pipelines move oil and gas fluids from processing facilities, storage etc., to transmission lines.
- Transmission lines: these are the main conduits for oil and gas transportation. They can be very large in diameter and very long (The US liquid pipeline system is over 250,000km in length). Natural gas transmission lines usually deliver to industry or to a distribution system: oil transmission lines carry different types of hydrocarbons to refineries or storage facilities.
- Product lines: pipelines carrying refined petroleum products from refineries to distribution centers.
- Distribution lines: these lines allow local, low pressure distributions from a transmission system.

Natural gas networks operate at different pressures: supra-regional transmission pipelines have a maximum diameter of 1.4 m and are operating at pressures higher than 100 bars. Such gas pipelines can cover distances of up to 6000 km (e.g. from west Siberia to Europe) (SYNER-G, 2010).

Supra-regional transmission pipelines are then separated into several branches of high-pressure pipelines (>70 bars). The high pressure pipelines distribute natural gas to several regions. Distribution pipelines are then used to serve the needs of communities. The pressure for these regional networks ranges from 1 to 70 bars, while local distribution systems usually operate in the medium (0.1 – 4 bars) or low pressure (< 0.1 bars) range (SYNER-G, 2010).

The natural gas pipeline network is the most extensive pipeline grid in Europe: it has a length of over 200,000 km in addition to more than 1.7 million kilometers of low-pressure distribution lines, which distribute over 300 billion cubic meters per year (SYNER-G, 2010). The transmission grid is made of steel:

it can have compressor booster stations to compensate for pressure drop caused by flow friction. The distribution pipeline system is usually made of polyethylene thermoplastics.

Oil pipelines are used for the transportation of hydrocarbons over long distances. A large segment of industry and millions of people could be severely affected by the disruption of crude oil supplies. In addition, the rupture of crude oil pipelines could lead to pollution of land and rivers. Crude oil and oil products are the fluids most extensively conveyed in European pipelines networks. There is an extended onshore network throughout the EU used for carriage of crude oil and refined products, including gasoline, kerosene, diesel and heavy fuel oils. The major EU traffic of crude oil and oil products takes place in France, Germany, Italy, Spain and the UK (SYNER-G, 2010).

The most common materials for hazardous liquid and gas pipelines are cast iron, steel and plastic. Cast iron has been largely used in the past. This material has shown high fragility and lacks ductility, which is an important safety requirement. Hazardous fluids and gas pipelines are nowadays made of ductile iron, steel and plastic materials, such as polyvinylchloride (PVC), polyethylene (HDPE) and glass reinforced fiber polymers. In particular, pipelines used for transmission systems are made of steel, and distribution pipelines are made of HDPE.

In terms of safety, the choice of the joints is a crucial issue. In order to avoid that the joints act as a point of weakness for the structure, they must be designed to maintain the continuity of the pipeline body in terms of strength and stiffness. The mostly used joints are welded, using different types of procedures and technology. Mechanical and special joint are used, as well (Lanzano et al., 2012).

The damage patterns occurring in pipeline systems are largely dependent on the material base and joints properties (Lanzano et al., 2012). All the possible combinations of materials and joints can be gathered in two categories: pipelines having rigid joints (i.e., strength and stiffness are more than that of the pipe barrel) are generally referred to as continuous pipelines (CP) (e.g. steel pipe with welded connection). Segmented pipelines (SP) consist of pipe segments that are connected by relatively flexible connections (e.g., cast-iron pipe with bell and spigot joints). Table II provides information on commonly used pipeline materials and joints. This approach has been adopted from the HAZUS approach, where the pipelines are divided into brittle (SP) and ductile (CP). The use of continuous pipelines which carry flammable and pollutant material is mandatory (CEN, 2006).

Table II. List of some commonly-used pipeline materials and joints (Lanzano et al., 2012)

Pipelines	Use	Materials	Joints
Continuous (CP) (Ductile)	Natural gas, oil, petroleum, water	Steel, Polyethylene (HDPE), Polyvinylchloride (PVC), Ductile Iron (DI), Glass Fiber Reinforced Polymer	Butt welded, Welded Slip, Chemical Welded, Mechanical joints or Flange joints, Special joints

<p style="text-align: center;">Segmented (SP) (Brittle)</p>	<p style="text-align: center;">Water, wastewater</p>	<p style="text-align: center;">Asbestos cement (AC), Reinforced concrete, PVC, Vitrified Clay, Cast Iron (CI), DI</p>	<p style="text-align: center;">Caulked joints, Bell end and Spigot joints, Seismic joints</p>
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2.3 Methodologies for seismic pipeline risk analysis

Currently, several authors have developed methodologies for seismic pipeline risk analysis. However, these frameworks usually refer to damage probability only and overlook the consequences of a possible release of hazardous materials. Moreover, most of these approaches do not consider specifically natural disasters as the triggering cause of the accidents, but consider only third party damage, therefore, they do not really address natech risk. Only recently, some authors have started addressing the development of natech risk assessment methodologies, however mostly for the chemical process industry. In the following, some examples are given in more detail.

Antonioni et al. (2009) carried out pioneering work on the development of a methodology for natech risk analysis. Based on the analysis of past accidents they developed a comprehensive general procedure for the analysis of the risk of accidents triggered by natural events in industrial facilities. This procedure has been applied to storage tanks at chemical facilities but can also be extended for pipeline natech risk analysis.

The procedure whose steps are shown in Table III was obtained as an extension of the scheme used for conventional quantitative technological risk analysis: specific steps, models and tools were introduced to extend the conventional procedure to also capture natech risk. In particular, specific damage models are required to understand the type and probability of equipment damage that may result in a release of hazardous material.

The starting point of this methodology is the analysis of natural hazards at the site of concern and the identification of the critical equipment that has the potentiality to cause a severe accident scenario due to the impact of a natural event. Later, the definition of damage states (DS) is used to compute the subsequent intensity of loss of containment and on the basis of the damage state identified, probabilities can be calculated. The consequence analysis for the reference scenario can be carried out using conventional models. This procedure considers also that more than one reference scenario may take place simultaneously due to the damage of more units. The final step allows the calculation of the risk indices with the additional contribution to individual and societal risk.

This analysis results in a series of fragility curves that correlate the system performance and relevant earthquake intensity measures.

Table III. Steps of the general procedure developed for the analysis of the risk induced by natural events in process facilities (Antonioni et al., 2009)

Nr.	Steps	Needs
1	Characterization of the external event	Frequency and severity parameters
2	Identification of target equipment	List of target equipment considered
3	Identification of damage states and reference scenarios	Event trees
4	Estimation of the damage probability	Equipment damage models
5	Consequence evaluation of the reference scenario	Consequence analysis models
6	Identification of credible combinations of events	Set of event combinations
7	Frequency/probability calculation for each combination	Frequency of event combinations
8	Consequence calculation for each combination	Overall vulnerability map
9	Calculation of risk indices	Overall risk indices

Santella et al. (2011) suggest an empirical estimation of the conditional probability of natech events with respect to different possible kinds of natural disasters: i.e., hurricanes, earthquakes, tornadoes, and floods at facilities covered by the US Toxic Release Inventory Program, the Risk Management Program, and onshore facilities engaged in oil and gas extraction (SIC 1311). Concerning earthquakes, natech accidents are analyzed considering the area impacted by the disaster. This area is then divided into one or more hazard zones based on the intensity of the hazard conditions experienced, i.e., Mercalli shaking intensity. Subsequently, the number of releases within each zone, aggregated by type of facility from which the releases occurred, are pooled to estimate the conditional probability of the release under the particular natural event. The results are shown as curves describing the probability of natech releases versus PGA.

Recently, Busini et al. (2012) proposed a short cut methodology for the analysis of industrial risks induced by earthquakes. The idea underpinning this method is to reduce the amount of time and expertise required in a traditional Quantitative Risk Analysis (QRA), trying to summarize in suitable Key Hazard Indicators (KHIs) the natech risk level associated with a given situation (i.e., a process plant located at a given position). The aim of such screening procedure is to answer a simple question: "Is the natech risk level associated with process plant A larger than the risk level associated with process plant B?". Answering this question requires simultaneous comparisons among a large number of different parameters, ranging from the type of hazardous substances present in the plant to the intensity of the external force, i.e., earthquake, each of which have different units of measurement. In order to evaluate the different risk levels corresponding to different individual risks using similar units, a short-cut methodology for the comparison and integration of natural hazards and suitable industrial risk indices

was developed. The Analytical Hierarchy Process was chosen to support decision making by establishing alternatives within a framework of multi-weighted criteria: it allows for a rational choice between alternatives on the basis of binary comparisons, i.e., comparisons involving only two elements at a time. Simple algebraic manipulations of these binary comparisons determine the weight for the various branches of the hierarchy. At the bottom of the hierarchy there are the alternatives that characterize the given plant with respect to the natech hazard. The consequences of the earthquake-related natech accidents are grouped into 3 main phenomena, and consequently three different hierarchies leading to 3 distinct indices related to fire, explosions and toxic dispersion. To determine the hazard level of a given plant, the three values are condensed into a global KHI which represents the overall hazard level in the KHI space.

2.3.1 Pipeline damage due to earthquakes

Underground pipelines and above-ground facilities present considerably different seismic response behaviors. Although buried structures are generally considered less vulnerable to seismic events than above-ground structures, severe consequences on underground pipelines were observed due to past strong seismic events. The seismic response of pipelines is dominated by soil deformation, so that vulnerability assessment strongly depends on the ground response evaluation: since the relative movement of pipes with respect to the surrounding soil is generally small, the structural response is dominated by the surrounding soil behavior (Scandella, 2007).

Scandella (2007) also notes that underground pipelines tend to move with the ground instead of vibrate independently and, due to their development in extended areas, the space variability of the seismic shaking plays a relevant role. As a consequence, it can be assumed that the structure is subjected to free-field stresses and strains due to the motion of the surrounding soil, while the relative movement of the structure with respect to the soil is generally negligible.

The seismic response of buried structures is usually described through displacements and deformations induced in the surrounding soil. Seismic effects are generally grouped in permanent ground deformations (PGD) and transient ground deformations (TGD). PGD typically occur in isolated areas of ground failure and they may be associated either to the direct seismic effects of surface faulting, or the induced effects of landslides, seismic settlement, and lateral spreading due to soil liquefaction. Transient ground deformations are due to the passage of seismic waves associated with strong shaking (Scandella, 2007). Transient effects, common to all earthquakes, are felt over a large geographical area and, even if the resulting damage is relative low if compared with the high damage rates due to permanent ground deformations, it may be relevant. The relative impact of different effects varies from earthquake to earthquake. There have been some events where lifeline damage occurred due to wave propagation alone. An example is the significant pipeline and tunnel damage in Mexico City caused by the 1985 Michoacan earthquake (Ayala and M.J. O'Rourke, 1989).

Typically, damage occurs due to a combination of effects. For instance, during the 1906 San Francisco event roughly half of the pipe breaks occurred within liquefaction-induced lateral spreading zones while the other half occurred over a somewhat larger area where wave propagation was apparently the

dominant cause (O'Rourke et al., 1992). The same pattern was observed after the 1999 Chi-Chi (Taiwan) event, when the water pipeline damage revealed the relative impact of different earthquake effects: half of the total damage was related to ground shaking, damage was also high (35 %) due to extensive faulting and large fault displacements, landslides were responsible for 11% of the damage because of the mountainous affected area, whereas liquefaction damage was relatively insignificant (2%) (Miyajima and Hashimoto, 2001).

The response of underground structures depends on various factors including the intensity of the earthquake, the geological conditions, the structure's location with respect to the fault (e.g. fault-crossing) or the structure's axis alignment with respect to the propagation direction of the wave field, and the structure's properties such as shape, extension, depth and mechanical-structural characteristics, which influence the strain state and the potential damage.

General observations can be made regarding the seismic performance of underground facilities, based on earthquake damage incurred by infrastructures during past earthquakes. Hashash et al. (2001) list the following points:

1. Underground structures suffer less damage than surface structures due to the confining pressure of the surrounding soil and the decreasing of the maximum displacements and accelerations with depth;
2. The response of underground lifelines is dominated by the surrounding ground response and not by the inertial properties on the structure itself;
3. The reported damage decreases with increasing depth of the soil layer above the infrastructure;
4. Underground facilities constructed in soft soils are expected to suffer more damage with respect to those in rock;
5. Lined and reinforced structures are less vulnerable than unlined and non-reinforced ones; stabilizing the surrounding soil and improving the soil-structure contact can reduce shaking damage;
6. Underground lifelines are more stable under symmetric load as it improves the ground-lining interaction;
7. Damage may be related to parameters which can be evaluated easily, such as PGA or PGV;
8. The duration of the seismic event is of crucial importance, because a long strong-motion shaking can cause fatigue failure;
9. Ground motion may be amplified upon incidence with a structure if incident wavelengths are 2-4 times the facility diameter.

In a seismic event, continuous and segmented pipelines have different failure modes. Continuous pipelines often fail due to tensile rupture, local buckling and beam buckling. The failure modes of segmented pipelines, especially of those with large diameters and thick walls, are tensile failure (axial pull-out), compression failure (crushing of joints), and circumferential flexure and joint rotation. In

segmented pipeline, failures are concentrated at the joints, however, continuous pipelines mainly fail due to the rupture of pipe barrel. For a detailed description of the different failure modes of both continuous and segmented pipelines the reader is referred to Dash and Jain (2007).

Studies based on the recorded number of repairs during past earthquakes do not always distinguish between leaks and breaks of the pipes. As a result, all fragility relations for pipelines are given for a single “failure” e.g., the repair rate (RR) per unit length of pipe. However, according to HAZUS (NIBS, 2004a), the type of repair or damage depends on the type of hazard: a pipe damaged because of ground failure is likely to present a break, whereas ground shaking may induce more leak-related damage. Based on these assumptions, HAZUS defines 3 categories of damage states (DS) (Table IV):

Table IV. Proposed damage states for pipelines (NIBS, 2004a)

	Damage state	Damage description	Serviceability
DS1	no damage	no break/leak	operational
DS2	leakage	at least one leak along the pipe length	reduction of the flow
DS3	failure	at least one break along the pipe length	disruption of the flow

2.3.2 Fragility estimation

A seismic fragility model describes the performance of an engineering component or system subject to earthquake excitations in probabilistic terms (Straub and Der Kiureghian, 2007). Fragility models are used to estimate the risk of the earthquake hazard acting on the components of lifeline systems such as oil, water and gas pipelines, electric power distribution systems, transportation networks and building systems. They are obtained either from statistical analysis of observed failures during past earthquakes (the empirical approach) or from structural modeling of the seismic performance of components and systems (Straub and Der Kiureghian, 2007).

Several approaches can be used to establish the fragility curves. They can be grouped under empirical, expert-judgment based, analytical and hybrid (Rossetto and Eknashai, 2003). Empirical methods are based on the observation of actual damage and on past earthquake surveys. They have the advantage of being based on real observed data and therefore consider seismo-tectonic and geotechnical conditions, as well as the characteristics of damaged structures. However, this means that these curves are specific to a particular site.

Expert-judgment based fragility curves rely on expert opinion and experience. Therefore, they are versatile and relatively fast to derive, but their reliability is uncertain because of their dependence on the experiences of the experts consulted.

Analytical fragility curves are based on the estimation of the damage distributions that are obtained through the simulation of an element’s structural response subjected to seismic action. This can result in a reduced bias and increased reliability of the vulnerability estimates for different structures compared

to expert opinion (Rossetto and Elnashai, 2003). Analytical approaches are becoming ever more attractive in terms of the ease and efficiency by which data can be generated.

Hybrid curves combine any of the above-mentioned techniques.

The study of past earthquakes and field surveys of actual damage of exposed elements allow compiling extensive statistics on the damage states of various typologies under earthquake loading. For instance, the study by Spence et al. (1992) yielded fragility curves for 14 classes of buildings, expressed as functions of macroseismic intensity. These results are based on a survey of 70.000 buildings subjected to 13 different earthquakes. Sabetta et al. (1998) also developed empirical fragility curves after studying data of 50.000 Italian buildings. The probability of exceeding a damage state is expressed with respect to PGA or spectral response parameters, which are converted from the observed macroseismic intensity. A similar work was performed by Rota et al. (2006) on Italian buildings. Finally, Rossetto and Elnashai (2003) developed empirical functions for various typologies of RC buildings (moment-resisting frames, infill walls, shear walls) from a database of 340,000 buildings exposed to 19 earthquakes. Empirical relations are also widely used to assess the vulnerability of components that are less prone to analytical developments than buildings, e.g. pipeline segments (ALA, 2001) or tunnels (Corigliano, 2007) and highway embankments (Maruyama, 2010).

A distinction can also be made between direct methods that yield fragility curves as a function of ground motion intensity measure types (e.g. PGA, PGV, Sa(T), etc.) and indirect methods that estimate the damage probability with respect to structural response parameters (e.g. spectral displacement at the inelastic period). The latter approach, used for instance in the framework of HAZUS (NIBS, 2004a) requires for each seismic scenario computation of the structural response with the capacity curve, and then evaluation of the damage probability using the associated fragility curves.

2.3.2.1 State-of-the-art of fragility curves for pipelines

In the following a state-of-the-art of fragility curves for pipelines is presented. Depending on geotechnical dynamics effects related to the pipeline damage, pipeline fragility relations are subdivided into two categories: ground failure (GF) and ground shaking (SGS) effects.

Seismic damage to pipelines is generally described through curves in which the performance indicator is expressed as a function of seismic intensity measure (intensity index in Table V). The performance indicator for pipeline damage due to the earthquake is generally given in the literature as “repair rate”, “damage rate” or “damage ratio”; other studies use the term “failure rate”.

Ground shaking effects (SGS)

Based on the literature review a total of twenty-six authoritative empirical studies relating pipeline damage to SGS effects were selected. A summary of these studies is displayed in Table V along with the strong motion parameter(s) used to describe the earthquake effect, the characteristics of pipelines and the number of earthquakes from which data have been obtained in each study. In addition, the reader is

also referred to Tromans (2004) and Pineda-Porras and Najafi (2010) provide thorough reviews of existing pipelines vulnerability studies.

Table V. Summary of selected fragility functions from the literature

Study	Pipeline Characteristics	Intensity Index	Nb of earthquakes
Katayama et al., 1975	-mainly CI pipes (water and gas distribution) -poor, average or good (soil) conditions	PGA	6
Katayama et al., 1977	-	PGA	6
Isoyama and Katayama, 1982	-mainly CI pipes	PGA	1
Eguchi, 1983	-AC, CI (welded-steel gas-welded joints, welded-steel arc-welded joints, welded-steel caulked joints)	MMI	4
Barenberg, 1988	-mainly CI pipes	PGV	3
Ballantyne et al., 1990	-	MMI	
Eguchi, 1991	-AC, CI, DI, PVC, polyethylene (welded-steel gas-welded joints, welded-steel arc-welded joints, welded-steel caulked joints)	MMI	4
O'Rourke et al., 1991	-	MMI	7
Hamada, 1991	-	PGA	2
O'Rourke and Ayala, 1993 NIBS, 2004a	-brittle (SP) or flexible (CP) pipes	PGV	6
Eidinger et al., 1995 Eidinger, 1998	-material type -joint type	PGV	7

	-diameter -soil type		
O'Rourke et al., 1998	-mainly CI pipes	PGV, PGA, MMI	4
Isoyama, 1998	-material type -diameter	PGV	1
Toprak, 1998	-no distinction	PGV	1
O'Rourke and Jeon, 1999	-mainly CI pipes -diameter	PGV	1
Eidinger and Avila, 1999	-material type -joint type -diameter -soil type	PGV	-
Isoyama et al., 2000	-DI, CI, PVC, steel, AC	PGA, PGV	1
ALA, 2001	-material -joint type -soil type -diameter	PGV	18
Pineda and Ordaz, 2003	-mainly brittle pipes (CI, AC)	PGV	1
O'Rourke and Deyoe, 2004	-mainly CI pipes	PGV	5
Pineda and Ordaz, 2007	-mainly brittle pipes (CI, AC)	PGV^2/PGA	1
Maruyama and Yamazaki, 2010	- CI, ductile cast iron, PVC (water distribution) -diameter	PGV	3
Lanzano et al., 2013a	-material (natural gas transmission and distribution)	PGV	40

	-joint type -diameter		
Lanzano et al., 2013b	continuous pipelines (CP), segmented pipelines (SP)	PGV, PGA	20

In the following, a summary of selected empirical relations is provided.

Katayama et al. (1975)

This study is an early attempt to establish a correlation between observed seismic damage of pipelines and a parameter of the ground motion (Figure 2).

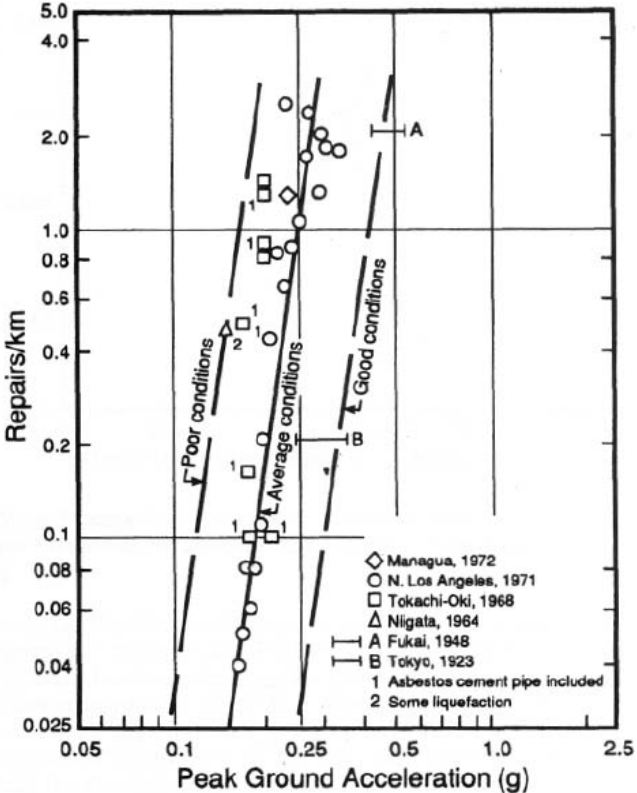


Figure 2. Pipeline fragility data of Katayama (1975) as presented in O’Rourke and Liu (1999).

It is based on pipeline failure rates obtained for six earthquakes: 1923 Kanto, 1948 Fukui, 1964 Niigata, 1968 Tokachi-Oki, 1971 San Fernando and 1972 Managua. A large scatter in the data is observed, probably due to larger damage rates induced in certain cases by permanent ground deformation. Most of the data presented is for cast-iron pipes although the data from the 1968 Tokachi-Oki earthquake

includes damage to asbestos-cement pipes. No distinction is made between pipe diameters, joint types or pipe material. However, in the fragility relationship Eq. (1),

$$RR = 10^{b+6.39 \log PGA} \quad (1)$$

a parameter b is introduced which depends on several factors like soil condition or pipe age. Depending on the “poor”, “average” or “good” conditions, this constant can take the values 4.75, 3.65 or 2.0, respectively (Ayala and Rourke, 1989). RR is the repair rate per km.

Eguchi (1991)

This study is an update of the earlier work of Eguchi (1983), based on damage data from four earthquakes: 1969 Santa Rosa, 1971 San Fernando, 1972 Managua and 1979 Imperial Valley. The study explicitly separates wave propagation damage from that induced by permanent ground deformation (O’Rourke and Liu, 1999) and a distinction is made between different pipe materials and joint types. The relationships shown in Figure 3 are bilinear with respect to macro-seismic intensity (Modified Mercalli Intensity), with damage rates increasing by about a factor of ten for a unit increase in MMI for $MMI < 8$, and doubling for a unit increase in $MMI \geq 8$.

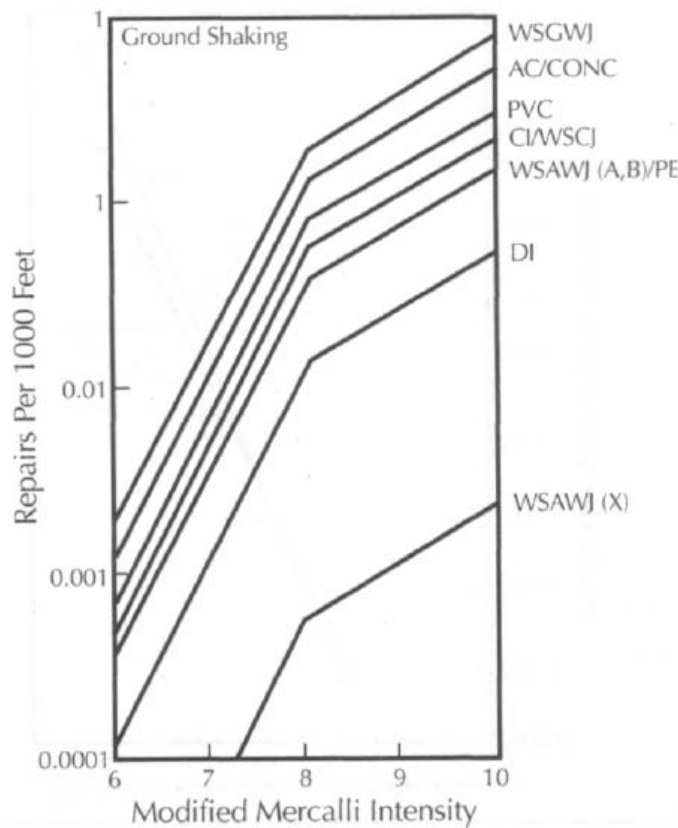


Figure 3. Bilinear pipeline fragility relations from Eguchi (1991). Note that repair rate is given per 1000ft (Reprinted from Eguchi (1991), Copyright (1991), with permission from Elsevier).

O'Rourke and Ayala (1993)

This study uses the original data from Barenberg (1988), plus three additional earthquakes: 1983 Coalinga, 1985 Michoacan and 1989 Tlahuac. The relationship was derived from eleven data points (A to K) and the trend line is plotted with respect to PGV (Figure 4). PGV was chosen as measure of the earthquake severity because it was observed that PGV values are more reliable due to the better availability of strong-motion records for earthquakes owing to the close relationship between PGV and ground strain. Katayama *et al.* (1975) and Barenberg (1988) both comment on PGA as not the best earthquake descriptor for determining ground shaking intensity.

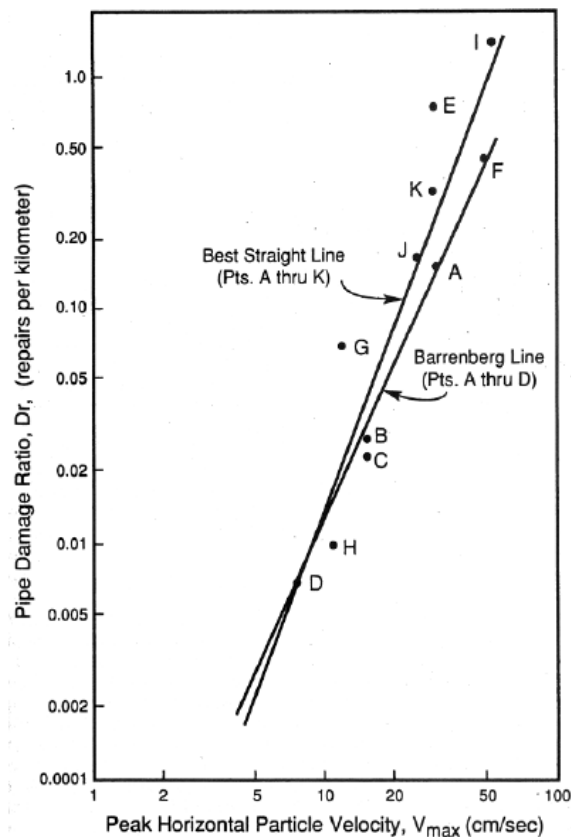


Figure 4. Fragility relations of Barenberg (1988) (derived from data points A-D) and O'Rourke and Ayala (1993) (derived from data points A-K) as presented in O'Rourke and Liu (1999).

The fragility equation is given by:

$$RR = 0.0001PGV^{2.25} \quad (2)$$

The fragility relationship of O'Rourke and Ayala (1993) was incorporated into the national loss estimation methodology used in the US, HAZUS (NIBS, 2004a). The relationship given in Eq. (2) is used for brittle pipes only as it is based on data from AC, concrete and CI pipes. For more ductile pipe types (steel, DI or PVC), HAZUS (NIBS, 2004a) suggests that this relation be multiplied by 0.3. Steel pipes with

arc-welded joints are classified as ductile whereas steel pipes with gas-welded joints are classified as brittle. In the absence of joint information, pre-1935 steel pipes are classified as brittle pipes. The HAZUS methodology does not consider pipe diameter as a factor.

Eidinger et al. (1995 and 1998)

The work of Eidinger et al. (1995) and Eidinger (1998) presents a fragility relationship for PGV based on the same data O’Rourke and Ayala (1993) used plus data points from the 1989 Loma Prieta earthquake. The pipeline data includes a number of factors of interest from the point of view of pipeline vulnerability: diameter, pipe material, lining, coating and data of installation. The data set and best-fit line through the data are shown in Figure 5 and the fragility relationship is given by the following equation:

$$RR = K_1 0.0001658 PGV^{1.98} \tag{3}$$

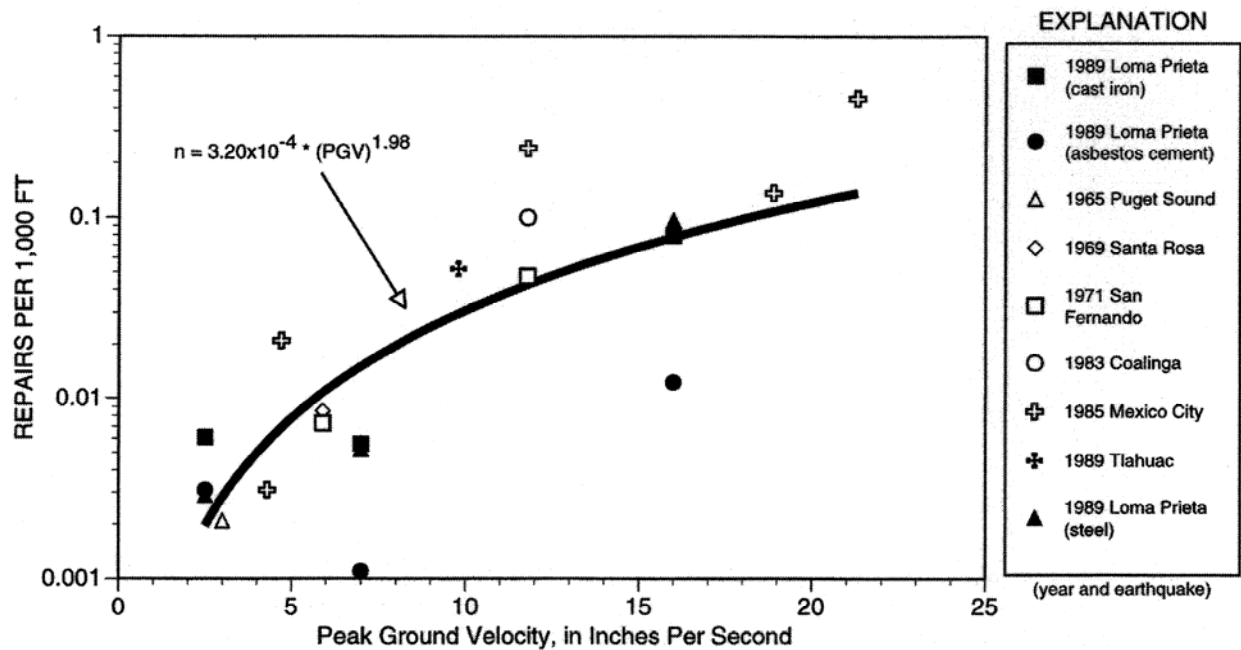


Figure 5. Fragility function by Eidinger (1998). Repair rate and PGV are both measured in imperial units

Eidinger et al. (1995) specify a modification factor, K_1 , to account for different combinations of pipe material, joint type and soil type. The range of K_1 values is summarized in Table VI.

Table VI. Values of the modification factor K_1 for different combinations of pipe material

Pipe material	Joint type	Soils	Diameter	K_1	Quality Index
CI	cement	unknown	small	0.8	B
	cement	corrosive	small	1.1	C
	cement	non corrosive	small	0.5	B

	rubber gasket	unknown	small	0.5	D
WS	arc welded	unknown	small	0.5	C
	arc welded	corrosive	small	0.8	D
	arc welded	Non corrosive	small	0.3	B
	arc welded	all	large	0.15	B
	rubber gasket	unknown	small	0.7	D
AC	rubber gasket	all	small	0.5	C
	cement	all	small	1.0	B
	cement	all	large	2.0	D
C	welded	all	large	1.0	D
	cement	all	large	2.0	D
PVC	rubber gasket	all	small	0.5	C
DI	rubber gasket	non corrosive	all	0.3	C

For the diameter values, "small" refers to pipe diameters $D < 30.48$ cm (12 inches); "large" refers to $D \geq 30.48$ cm. Each K_1 value is classified according to a data quality index, which describes the confidence in the current empirical data set. Each level has an approximate qualitative description:

B - "there is a reasonable amount of backup empirical data and study"

C - "limited empirical data and study"

D - "based largely on extrapolation and judgment, with very limited empirical data".

Isoyama et al. (2000)

The work of Isoyama et al. (2000) is based on earlier studies of the 1995 Kobe earthquake. The pipeline fragility relationships were derived using the following functional forms (Eqs. (4) and (5)):

$$R_m(IM) = C_p \cdot C_d \cdot C_g \cdot C_l \cdot R(IM) \quad (4)$$

where $R_m(IM)$ is the pipeline repair rate per km of pipe as a function of the intensity measure parameter IM , C_p , C_d , C_g , and C_l are correction coefficients for the pipe material, diameter, geological condition, and liquefaction occurrence, respectively. IM is the peak ground velocity (PGV) and $R(IM)$ estimates the damage ratio for cast-iron pipes with a certain diameter:

$$R(IM) = a(IM - IM_{\min})^b \quad (5)$$

Parameters a and b are regression coefficients and IM_{\min} is the minimum value of strong ground motion for which damage is considered to occur. The repair rate as a function of PGA and PGV is shown in Figures 6a and 6b, respectively. The fragility relations are based on 19 data points and 16 data points respectively. In each case, several additional outlying points were excluded due to extreme instances of liquefaction or topographic effects.

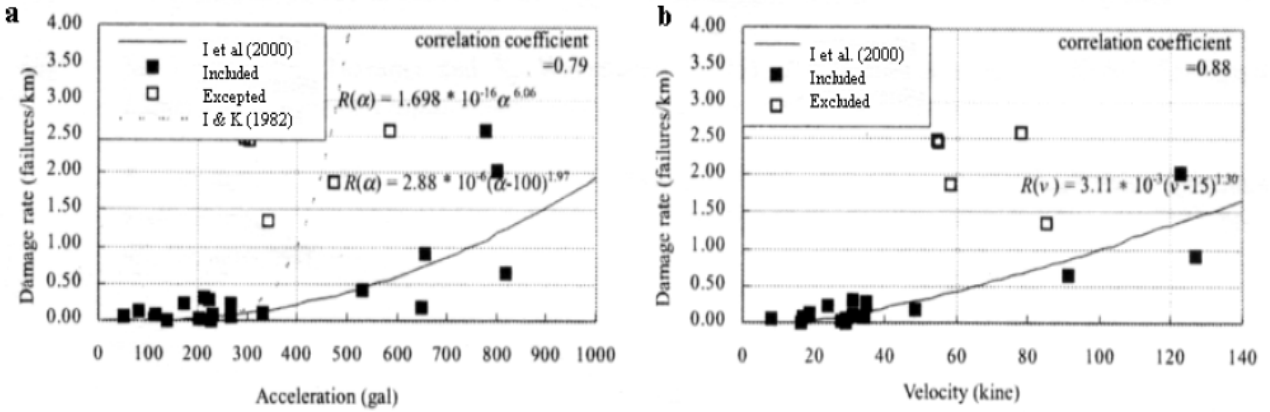


Figure 6. Data sets and fragility relations from Isoyama et al. (2000); a) acceleration scale is PGA (1gal = 1cm/s²); b) velocity scale is PGV (1 kine = 1cm/s). Solid squares indicate data points included in the regression while. Open squares indicate outliers excluded from the data set.

ALA (2001)

In 2001, the American Lifelines Alliance (ALA), published a set of detailed procedures to evaluate the probability of damage from earthquake effects to various components of the water supply system (ALA, 2001). In the work were included water distribution systems (pipelines, tunnels and canals), aboveground cylindrical storage tanks and portions of the conveyance control and data acquisition system (SCADA) that are located along the conveyance system, and flow control mechanisms (e.g. valves and gates). For each component, the likely damage states and corresponding fragility functions were presented. For buried pipelines, fragility relations were developed separately for permanent ground deformation effects and ground shaking effects. For each data point, pipe material, pipe repair rate (RR), pipe diameter, PGV and are specified. Pipe material and pipe diameter categories are summarized in Table VII and the full data set of ALA is presented in Figure 7.

Table VII. Pipe characteristics included in the dataset for ALA (2001) fragility relation (percentage subject to rounding errors).

Pipeline characteristic	Category	Description	Percentage of total database
Material type	AC	Asbestos Cement	12.3
	CI	Cast Iron	46.9
	CP	Concrete	2.5
	DI	Ductile Iron	11.1
	MX	Mixed (CI & DI combined)	11.1
	S	Steel	16.0
Diameter	DS	Distribution system (mainly small diameter)	70.3
	LG	Large diameter (> 30.48 cm)	9.9
	SM	Small diameter (≤ 30.48 cm)	19.8

Figure 7 shows the standard “backbone” fragility relationship based on a single-parameter linear model and lines representing the 16th and 84th percentiles of the data set. The “backbone” line defines the median slope of all 81 data points and has the property of having equal numbers of points above and below it. This approach, which is less sensitive to data outliers and describes the central tendency, was chosen in preference to a least-squares best fit line due to the amount of scatter in data set.

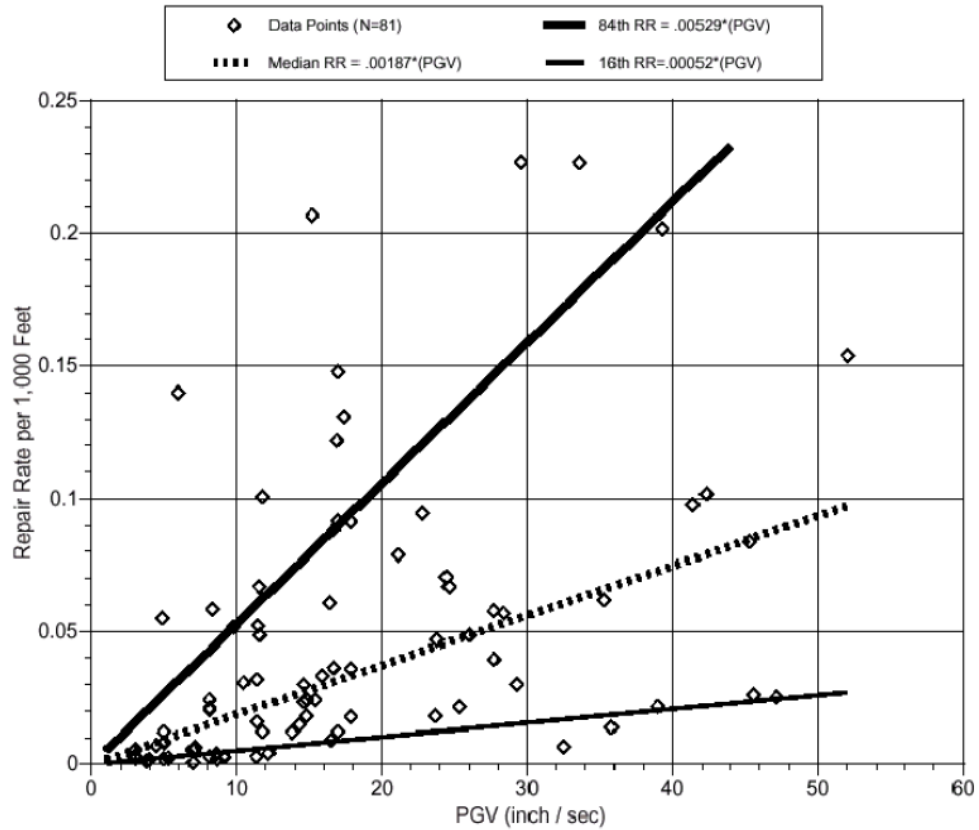


Figure 7. Data set used by ALA (2001) to derive a pipeline vulnerability function for PGV.

Ground failure effects (GF)

The modeling of SGS effects is more straightforward than that for ground failure effects. From a natech risk analysis point of view we will therefore in a first step give priority to assessing the impact of SGS on industrial systems. Nonetheless, this literature review has identified 8 studies related to GF impact, which are briefly summarized in Table VIII.

Table VIII. Summary of the fragility functions from the literature with respect to GF

Study	Type of material	Proposed severity-impact relationship
Eguchi, 1983	-AC, CI (welded-steel gas-welded joints, welded-steel arc-welded joints, welded-steel caulked joints)	See Figure 15 in the reference
Honneger and Eguchi, 1992 NIBS, 2004a	-ductile (steel, DI, PVC) or brittle (AC, concrete, CI)	$RR=K*7.821PGD^{0.56}$ $K = 0.3$ for flexible pipes
Ballantyne and Heubach, 1996	-material: WS, old steel and CI, locked converse, AC, CI	Relative vulnerability – see in the reference
Eidinger and Avila, 1999	-ductile	$RR=K_223.674^{0.53}$
ALA, 2001	-material -joint type	$RR=K_211.223PGD^{0.319}$
Terzi et al., 2007	-segmented pipes	$RR=3.2103PGD^{0.4103}$
Lanzano et al. 2013b	Continuous pipelines (CP), segmented pipelines (SP)	$RR=aPGD^b$ – see table 4 in the reference for values of the constants a and b

The empirical fragility curve proposed by Eguchi (1983) is shown in Figure 8. Attention has focused on PGD induced by fault ruptures or landslides. These hazards are indeed likely to induce high strains, as opposed to spatially distributed deformations induced by ground shaking.

The study by ALA (2001) is based on engineering judgment. Like for wave propagation related damage, the proposed “backbone curve” can be modified by a corrective factor K_2 according to the pipe’s material and joint type. The different values are presented in Table IX.

Table IX. Values of the corrective K_2 according to ALA (2001)

Pipe material	Joint type	K_2
Unknown	Unknown	1.0
CI	Cement	1.0
	Rubber gasket	0.8
	Mechanical restrained	0.7
WS	Arc-welded, lap welds	0.15

	Rubber gasket	0.7
AC	Rubber gasket	0.8
	Cement	1.0
Concrete	Welded	0.6
	Cement	1.0
	Rubber gasket	0.7
PVC	Rubber gasket	0.8
DI	Rubber gasket	0.5

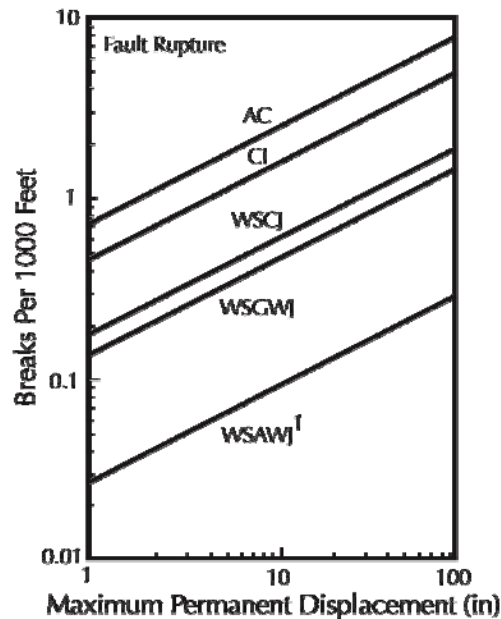


Figure 8. Fragility relations proposed by Eguchi (1983) for fault ruptures as presented in O'Rourke and Liu (1999). WSGWJ: welded steel gas-welded joints, WSAWJ: welded steel arc-welded joints, WSCJ: welded steel caulked joints

2.3.2.2 Studies including natech-related aspects

The previous studies present empirical expressions on the repair rate for pipelines as a function of the intensity measure. Therefore, these studies are mainly useful for estimating losses due to damage and business interruption.

In these studies, the approximated correlations between damage patterns (breaks or leaks) and geotechnical aspects (SGS or GF) result in an emphasis on the different kinds of damage and on their probability. However, they do not consider the risk of hazardous-materials releases from pipelines, fires or explosions. Moreover, most of the fragility formulations are derived for segmented pipelines, because they all are generally based on data obtained from post-earthquake data of water and wastewater systems (ALA, 2001) while oil and gas pipelines would be continuous systems.

Due to these limitations, the natech risk assessment of pipelines requires further model development and fragility formulations based on different specific indicators, the specific level of damage and specific curves for each type of geotechnical and structural pipeline aspect (Lanzano et al., 2012).

Four studies addressing natech risk in pipelines are discussed in more detail in the following.

Lanzano et al. (2012, 2013b)

Recalibrating the simplified classification of HAZUS (NIBS, 2004a), Lanzano et al. (2012, 2013b) identified three damage indicators DS (Table X) describing the type of structural damage to pipelines.

Table X. Damage state DS for pipelines as proposed by Lanzano et al. (2013b)

States	Damage	Patterns
DS0	Slight	No damage; pipe buckling without losses; damage to the support of aboveground pipelines without damage to the pipeline
DS1	Significant	Pipe buckling with material losses; longitudinal and circumferential cracks; compression joint break
DS2	Severe	Tension cracks for continuous pipelines; joint loosening in the segmented pipelines

The possible negative effects on the population and the environment, derived from the release of content from the damaged pipe, were then combined into three different risk states (RS) (Table XI).

Table XI. Risk states RS for pipelines as proposed by Lanzano et al. (2013b)

States	Risk	Loss of containment
RS0	Null	No loss of fluid from damaged pipeline
RS1	Low	Limited, time-distributed loss of hazardous substance
RS2	High	Large loss of hazardous substance (e.g. entire tube surface)

The RS levels were organized in order to match the corresponding damage state. For example, state RS0 corresponds to DS0, in which the damage type does not cause any loss of containment.

Based on the collected data and on the observed behavior of pipelines, Lanzano et al. (2013b) defined four possible classes of fragility curves: a) continuous pipelines CP under strong ground shaking SGS; b) continuous pipelines CP under ground failure GF; c) segmented pipelines SP under strong ground shaking SGS; d) segmented pipelines SP under ground failure GF. The reference intensity parameter is PGV for SGS cases (Figure 9a) and PGA for GF cases (Figure 9b).

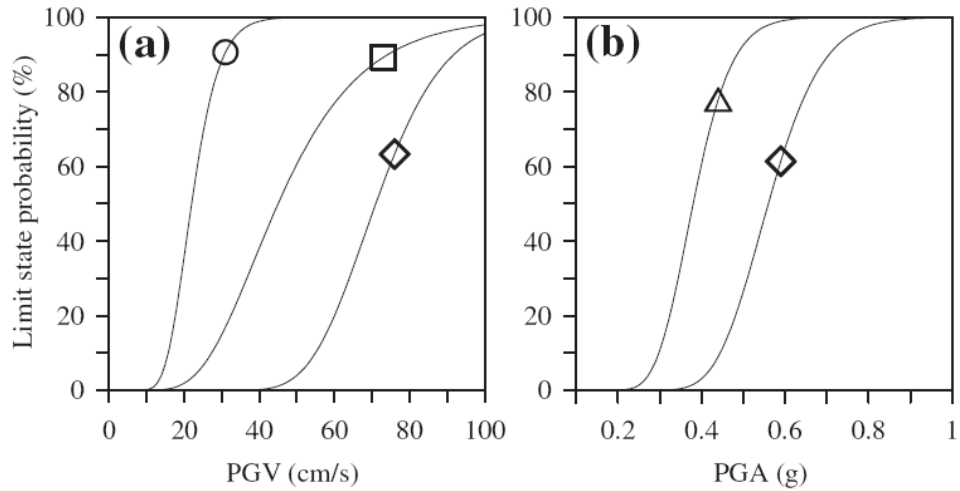


Figure 9. Fragility curves for buried pipelines under SGS (a) and GF (b) in terms of limit state probability percentage for the RS state: \square : CP RS \geq RS1; \diamond : CP RS=RS2; \circ : SP RS \geq RS1; Δ : SP RS=RS2 (Reprinted from Lanzano et al. (2013b), Copyright (2013), with permission from Elsevier).

In addition, in order to obtain univocal threshold values both for PGV and PGA with reference to the RS states, the seismic vulnerability is also presented as a probit function (Figures 10a and b).

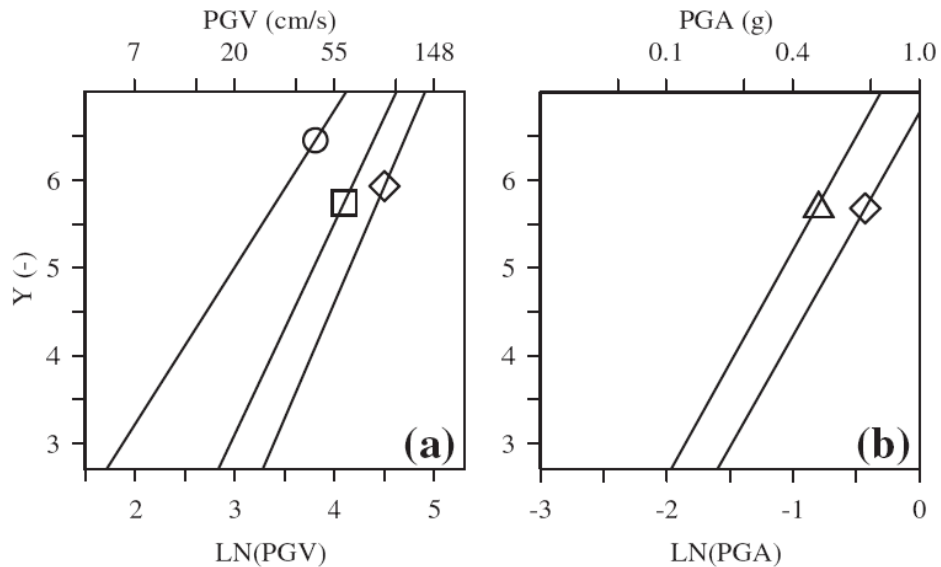


Figure 10. Probit curves for buried pipelines under SGS (a) and GF (b). RS state: \square : CP RS \geq RS1; \diamond : CP RS=RS2; \circ : SP RS \geq RS1; Δ : SP RS=RS2 (Reprinted from Lanzano et al. (2013), Copyright (2013), with permission from Elsevier).

Omidvar et al. 2013

These authors propose a damage analysis of buried fuel pipeline systems and assess the probability of consequences of hydrocarbon releases from the pipelines considering that the presence of aerial power

distribution lines could cause ignitions and generate widespread fire. Two different earthquake scenarios were considered and for each segment of pipeline that experienced a leak or break, the probability of ignition was calculated using logic trees. In addition, in the ignition model the presence of different fuel materials was considered, as well as the probability of formation of flammable mixtures of oil and products and oxygen or other flammable materials.

This analysis resulted in the assessment of the risk of pipeline ignition and exposure of the surrounding areas to explosions presented in the form of maps. One of the two considered scenarios is shown in Figure 11.

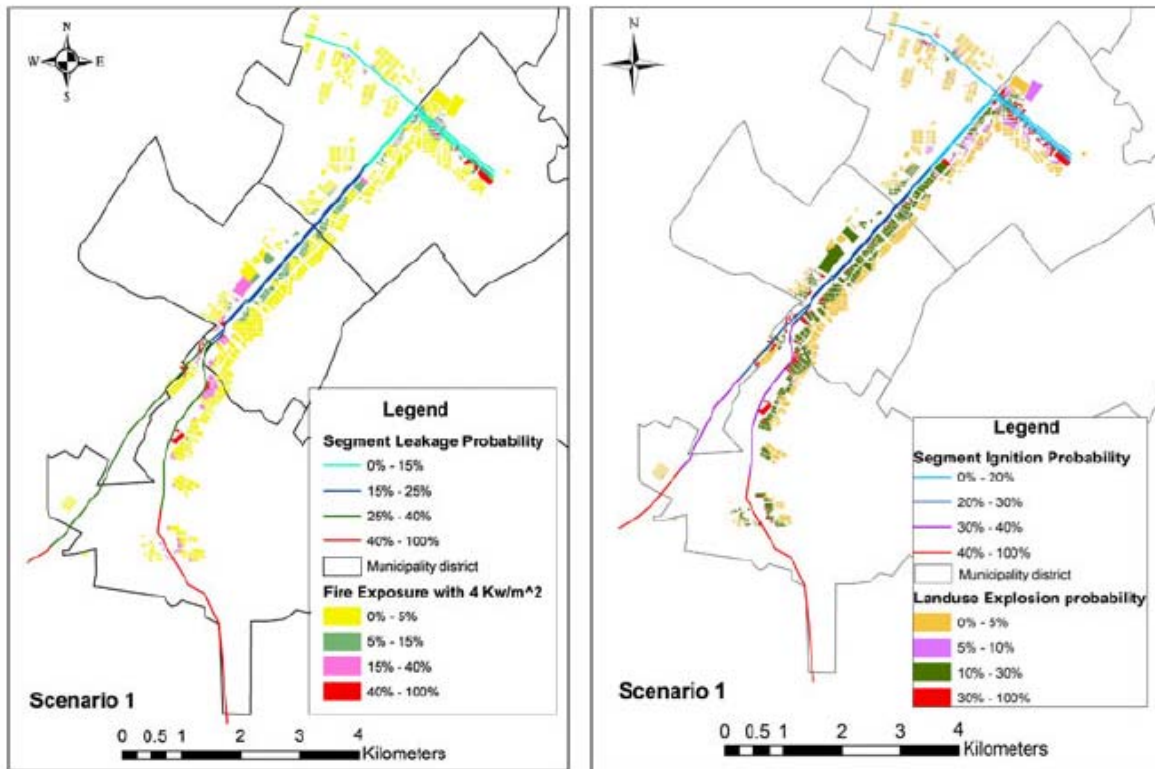


Figure 11. Probability of pipeline leakage and risk of exposure to fire of the adjacent land (left). Risk of pipeline ignition and risk of exposure to an explosion (right) (Reprinted from Omivdar et al., (2013), Copyright (2013), with permission from Springer).

Dziubinski et al. (2006)

As one of only a few studies related to pipeline Natch risk, Dziubinski et al. (2006) propose a methodology for the analysis of risks related to hazards associated with dangerous substance transport in long pipelines. A specific feature of this methodology is a combination of qualitative and quantitative techniques used to determine pipeline failures and their probable consequences, taking individual and societal risk into account. This analysis results in the evaluation of a hazard zone and in the F-N curve and the calculation of the probabilities of specified consequences.

Jo and Ahn (2005)

Jo and Ahn (2005) propose a risk analysis for natural gas pipelines in terms of fatal length and cumulative fatal length. This analysis considers third party damage, among which earthquakes are listed, and studies their consequences on the population. Although the authors do not provide a relationship between the intensity measure that describes the earthquake and the consequences (fragility curve) they consider the consequences of releases in their work.

3. Vulnerability of pipelines to floods

Numerous severe accidents highlight the risk associated with floods impacting pipelines transporting dangerous substances. One major accident in the San Jacinto River Valley in 1994 was already mentioned in the introduction.

More recently, in June 2013, parts of Alberta (Canada) were under a state of emergency because of a 100-year flood event. Two pipeline leaks were directly linked to the heavy rains: in the Turner Valley, a pipeline carrying sour gas containing one per cent hydrogen sulfide was ruptured by floating debris, prompting the evacuation of residents within a 100-mile radius. Although the operator Legacy Oil and Gas shut the line off from the source, it was impossible to access the line itself due to deepening flood waters (DeSmog Canada, 2013). In northeast Alberta, the Canadian pipeline company Enbridge Energy closed its Wood Buffalo pipeline system in response to a spill from its line 37. About 730 barrels of crude oil spilled from line 37. Enbridge said that no potable water wells were affected by the release although some oil spilled into a small creek and a lake. There have been reported impacts from the flood involving exposed pipelines caused by erosion or rerouting of waterways (UPI, 2013).

Floods are among the most frequent natural hazards that trigger technological accidents (Krausmann and Baranzini, 2012) and pipework was found to be very vulnerable to flood effects, often leading to loss of containment and possible reaction of the released chemicals with water (Cozzani et al., 2010). Nevertheless, only very few dedicated studies can be found on the impact of floods on pipelines in the scientific literature. This lack of studies can partially be ascribed to the fact that often “flooding” is seen as a secondary phenomenon, due to rain or other natural hazards, for example hurricanes.

During floods, the extreme forces of the floodwaters, heavy floating debris, natural erosion and water pressure from high water can adversely affect pipelines. Moreover, flood waters change the landscape, and pipelines may become susceptible to damage: for instance, during inspections following pipeline ruptures beneath the Yellowstone River, pipeline operators observed that the river seemed to be carving a deeper channel, leaving the arteries of the pipeline exposed (TRP, 2011).

This topic is nowadays becoming a great concern due to the high frequency of severe flooding events. In 2011, the Pipeline and Hazardous Materials Safety Administration of the US Department of Transportation issued an advisory bulletin to all owners and operators of gas and hazardous liquid pipelines to communicate the potential for damage to pipeline facilities caused by severe flooding. This

advisory includes recommended industrial facility planning procedures that operators should consider taking to ensure the integrity of pipelines in case of impending or extreme flooding (PHMSA, 2011).

Because of the scarcity of data specifically dedicated to pipelines, a review of the literature on damage of industrial items due to flood events is presented in the following sections.

3.1 Flood severity measures

The consequences of flood damage in pipelines or industrial equipment are the results of the interaction of a number of flood characteristics with the system under study. The most important identified factors are: water depth, flow velocity, duration of the inundation and sediment or debris load and the interaction of these factors with the system.

The characterization of the flood event requires the assessment of frequency and severity of the floods. The standard parameter for the frequency is the return period (T_r) measured in years and given by hydrological studies. Since there are different kinds of flood events, for example floodplain inundation with high water level or flash flood with high water velocity, it is necessary to distinguish the possible modalities of flood impact (slow submersion, moderate speed wave, high speed wave). From this standpoint, the flood severity can be quantified by two parameters: water depth and water speed. Nevertheless these parameters are usually not reported in general flood hazard assessment studies and are not available unless specific analyses were performed for a given site (Campedel et al., 2009).

Numerical simulation can help to model the flood dynamics, by computing high flow velocities and high water level conditions which can be assumed as threshold limit values for structural damage with loss of containment and subsequent release of hazardous materials (DCP, 2003). For instance, the value of the severity parameters allows the computation of the overall pressure acting on process equipment on the basis of hydrostatic pressure.

3.2 Methodologies for pipeline risk analysis with respect to floods

Concerning risk analysis with respect to floods, much of the research present in the literature is dedicated to housing risk assessment. Few studies address industrial plants (Su et al., 2009; Booyesen et al., 1999), chemical plants (Campedel et al., 2009, RiskScape, 2005, Krausmann and Mushtaq, 2008), or natech risk analysis (Rota et al. 2008; Cozzani et al., 2010, Santella et al., 2011) and very little has been found specifically applied to pipelines (NIBS, 2004b; Chisolm and Matthews, 2012).

Three general frameworks of risk analysis related to floods events exist in the literature and have already been introduced in section 2.3, applied to earthquakes. They are 1) the empirical estimation of the probability of a natech event, as e.g. presented in Santella et al. (2011), 2) the short-cut methodology proposed in Busini et al. (2011) and applied in Rota et al. (2008) and 3) the general natech risk analysis methodology proposed in Antonioni et al. (2009) and applied in Campedel et al. (2009).

3.2.1 Pipeline damage due to floods

When determining the general damage caused by floods, a distinction can be made between three different categories of damage: direct material damage, direct damage due to business interruption and indirect damage. Direct material damage refers to the damage which is caused to objects, capital goods and movable goods as a result of direct contact with water (NIBS, 2004b). This includes:

- Cost of damage repair to immovable property (land and buildings) rented or in ownership: land and buildings;
- Cost of damage repair to means of productions, such as machinery, equipment, process plant and means of transport;
- Damage to property contents;
- Damage due to the loss of moveable property, such as raw materials, auxiliary materials and products (including damage to harvest).

The second category of direct damage is defined as damage due to business interruption, i.e. the commercial losses caused by lost production. Finally, indirect damage comprises the damage to business suppliers and customers outside the flooded area and travel time losses due to inoperability of roads and railways in the flooded area (NIBS, 2004b).

A survey from Chisolm and Matthews (2012) highlights the short- and long-term impacts of flooding on utility infrastructure systems. The impacts of large-scale disasters such as flooding can be quite apparent after the event, but the effects on buried pipelines are less obvious at the time of the disaster and can have long-term effects on the buried systems.

Two types of flooding were considered in the survey: flooding following a hurricane and non-coastal-type flooding. The survey focused on the water and wastewater system, as well as on the gas system. It concludes that gas pipes incurred the same type of damage as other service pipes.

The most common damage from storm-surge type flooding to buried infrastructures reported were the separation of pipe joints, leaks and breaks (Chisolm and Matthews, 2012). Pipe collapse was observed, too. The damage was mainly caused by ground subsidence and loss of bedding. Flooding caused supporting soil to become supersaturated, and when the floodwaters drained, the supporting soil began to shrink and subside. The movement of the soil led to breaks and the shifting of fractures, causing fracturing of connected service pipes.

During non-coastal-type flooding, damage occurred at connection points – for instance where pipes and casting joined manholes or inlets. Some damage was also observed in older sections of PVC and reinforced concrete pipes. This damage was associated with high internal velocities and pressurization. In many cases, water had flown backward in gravity storm-water pipes. In-situ clay around the pipes was saturated to the point where the soil flowed into the pipes as the water drained from the system. This

caused a loss of soil around the pipes and significantly decreased pipe support, manholes and other elements.

In addition to the short-term impacts, the areas affected by flooding can experience long-term impacts in the months and years following the event. Chisholm and Matthews (2012) identified voids around the pipes created by the floods and subsequently dangerous sinkholes. Another long-term impact to the underground infrastructure was accelerated degradation of the system and its components, resulting in failures before the end of service life of the various components. Structural damage, loss of bedding support and an increase in corrosion rate all contribute to the accelerating ageing of underground pipelines.

From a natech point of view, in the case of flood events the identification of potential damage to equipment and to structures is possible only at a simplified level. Unfortunately, there are no sufficient data to adequately define the damage states and subsequently their probability of occurrence (Campedel, 2008).

3.2.2 Fragility estimation

Given that very few studies are dedicated to the analysis of pipeline damage caused by floods, in this section a list of the most relevant studies related to damage caused by floods to industrial facilities is provided.

In flood risk analysis, depth-damage curves, also known as loss functions, are used as “fragility curves”. The purpose of a depth-damage curve is to relate damage and depth of flooding while the target property is being flooded. First suggested by White (1964), these curves are a synthetic way to represent damage but they often ignore factors such as the speed of flood, the span of flooding, debris transportation or mud accumulation by flood.

There are two ways of deriving depth-damage curves: one relies on the statistical analysis of damage data collected after floods; the other is based on simulations of the flooding condition and generates synthetic depth-damage curves (Smith, 1994; Dutta et al., 2003).

Black (1975)

Black’s curves were developed in 1975 as a part of ‘Project Agnes’, a multidisciplinary investigation of flood risk management produced for the US Department of Commerce. The curves are based on the fact that a flooded house is subjected to buoyancy, hydrostatic pressure and dynamic pressure. Buoyant forces were calculated by Black (1975) for four houses at rising water levels. Once buoyant forces at different depths were calculated, Black assessed the horizontal force on the houses due to the flowing water. When the force due to the flow equaled the frictional force available to keep the house on its foundations the building was deemed to have failed. Threshold velocities were calculated for various depths, and plotted on a graph with a velocity axis and a water depth axis, as can be seen in Figure 12. For combinations of depth and velocity that fall “inside” the curve (i.e. closer to the origin), the structure

is considered stable and will remain on its foundations. In contrast, if a point lies “outside” the curve, the structure is considered to have failed.

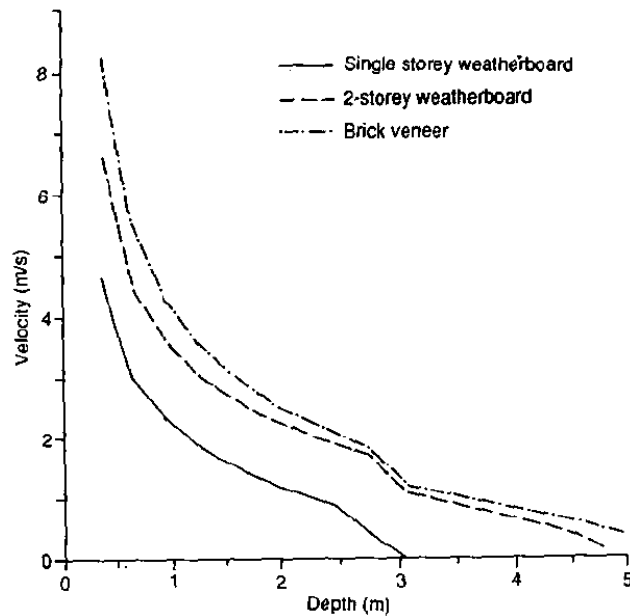


Figure 12. Critical velocity and depth for building failure for different depth of inundation and residential building type (Black, 1975)

Booyesen et al. (1999)

This study proposes a way to develop a standard flood-damage function for industries. Starting from a completed questionnaire at every industrial plant, four sets of basic information are identified: the description of the location of the industrial complex, the characteristic of the flood plain in order to evaluate which part of the plants will be more damaged, the economic evaluation of contents and production of the damaged structures, and the selection of appropriate unit damage functions, expressed in terms of loss of profit allocated to the different structures, contents and production. Damage for each considered part is then added up to constitute an artificial damage function.

Su et al. (2009)

Su et al.(2009) identify four classes of industrial and commercial activities and two groups of flood damage data based on the flood depth: high and small amounts of damage. Damage is measured in terms of economic losses.

RiskScape (2010)

RiskScape is a tool that provides a framework for calculating the risk of impact to assets from different types of natural hazards. In the tool, depth-damage functions, also called stage-damage curves or

fragility curves, are the most common method to estimate potential direct damage costs. RiskScape's fragility curves typically relate the percentage damage (relative to replacement cost) for a variety of elements such as buildings, cars, household goods, relative to flood characteristics such as inundation depth, velocity or duration.

Fragility functions are typically based on either empirical curves developed from historical flood and damage survey data or synthetic functions (hypothetical curves) based on expert opinion developed independently from specific flood and damage survey data.

Both methods have their advantages and disadvantages (Middelmann-Fernandes, 2010). RiskScape uses a combination of both as it has been found that synthetic damage curves calibrated against observed flood damage gave the most accurate results (McBean et al., 1986). As damage to buildings typically makes up the most significant proportion of direct damage costs, the initial project focus was on buildings and their contents, but progress in other categories is also being made.

Within RiskScape at present the potential to assess direct damage to lifeline infrastructure is limited to the road network and the water and wastewater system.

USACE (2010)

The US Army Corps of Engineers (USACE) report suggests the introduction of fragility curves in flood risk assessment. Inspired by the development of fragility curves in seismic events, they examine what methods are used in those fields in order to identify what method could be more appropriate for flood events.

Santella et al. (2011)

These authors propose an empirical estimation of the conditional probability of a natech event triggered by floods at chemical facilities. In this study, 10 flood events among the most severe flood disasters in the USA in the last decades were analyzed. The "conditional probability of natech" is calculated as the number of hazardous-materials releases per facility exposed to a flood and refers to the probable number of natechs that will occur in a specific location as a result of the realization of the natural disaster. In particular, in this analysis flood characteristics such as flood depth were not taken into account.

Krausmann and Mushtaq (2008)

Krausmann and Mushtaq (2008) investigate the risk associated with the flooding of industrial installations and analyze qualitatively the potential impact in terms of the potential release of hazardous materials. Based on expert judgment they propose a qualitative scale linking the flood intensity (water depth and speed, duration) to the level of potential damage.

Antonioni et al. (2009)

Having developed a general methodology for the quantitative analysis of natech risk for the process industry, these authors apply their methodology to earthquake and flood impact. They define damage state categories that are then linked to release states that provide a measure of the associated risk of the loss of containment (Table XII). They also define a simplified relationship between damage probability and the water height, as well as the square of the water speed.

Table XII. Damage states and associated release categories for atmospheric and pressurized storage tanks

Damage state	Release state
Failure of flanges and connections	Continuous release from a hole with an equivalent diameter of 10mm
Failure of roof or shell fracture	Continuous release of the complete inventory (in more than 10 min)
Impact of adjacent vessels or with trailed objects	Instantaneous release of the complete inventory (in less than 2 min)
Catastrophic collapse	Instantaneous release of the complete inventory (in less than 2 min)
Shell fracture (only for pressurized tanks)	Continuous release of the complete inventory (in more than 10 min)

Landucci et al. (2013)

Landucci et al. (2013) developed a mechanical model to describe the flood impact and the possibly resulting damage on storage tanks. The model is based on a simplified description of flood intensity and was applied to assess the vessel damage probability. The critical filling level was identified as the key operating parameter for measuring tank resistance. Different curves (an example is shown in Figure 13) were obtained to establish the vulnerability of the tank as a function of the density of the fluid contained in the vessel and of the physical properties of the flood, i.e. depth and velocity.

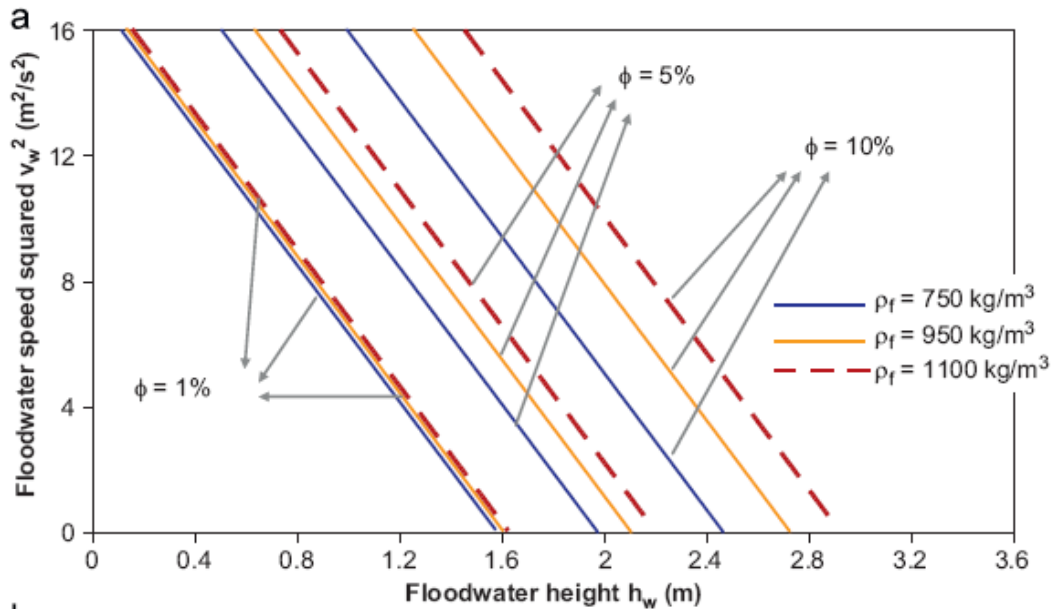


Figure 13. Example of a failure chart for a vessel of a specific configuration: ϕ is the operative filling level, ρ_f is the density of the stored fluid (Reprinted from Landucci et al. (2013), Copyright (2013), with permission from Elsevier).

4. Conclusions

The retrospective analysis of accidents highlighted that pipelines and pipes in general are vulnerable to the impact of natural disasters. A review of the literature on analysis of pipeline natech risk due to earthquakes and floods was carried out in view of the development of a dedicated pipeline natech risk analysis methodology for implementation in the RAPID-N tool.

The literature on seismic risk analysis offers the largest number of examples and methodologies, whereas very little work was found on flood natech risk analysis and equipment vulnerability models. From the standpoint of natech risk analysis, the results of this work can be summarized in the following points:

- the interaction between natural and industrial hazards needs to be analyzed in a proper quantitative risk assessment framework, which needs to include the characteristics of natech accidents such as the characterization of the triggering natural hazard or disaster and the final accident scenarios;
- fragility curves are a fundamental instrument for the evaluation of the damage or probability of damage associated with a seismic event. The majority of the examples report a relationship between the intensity measure of the catastrophic event and the damage but overlook the possible release scenarios and consequences subsequent to a loss of containment event;

- existing studies on flood risk analysis lack a proper characterization of damage related to flood characteristics.

In addition, the literature review showed that most studies on seismic risk concentrate on buried pipelines and ignore above-ground structures. Moreover, the analysis of past accidents does not distinguish between pipelines transporting hazardous materials and water pipelines. In the latter case the possibility of a natech event is not considered. This empirical data can be useful for equipment vulnerability model development if the boundary conditions are similar, but it cannot be used for consequence assessment.

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Abstract

Natural events, such as earthquakes and floods, can trigger accidents in oil and gas pipeline with potentially severe consequences to the population and to the environment. These conjoint technological and natural disasters are termed natech accidents. The present literature review focuses on the risk analysis state-of-the-art of seismic and flood events that can impact oil and gas transmission pipelines. The research has focused on methodologies that take into account the characteristics of natech events: for instance, the characterization of the triggering natural hazard and the final accident scenarios, as well as fragility curves for the specific assessment of the potential consequences of natech accidents. The result of this research shows that the literature on seismic risk analysis offers the largest number of examples and methodologies, although most studies focused on structural damage aspects without considering the consequences of a potential loss of containment from the pipelines. Very little work was found on flood risk assessment of natech events in pipelines.

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