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Performance Assessment of Continuous Buried Pipelines Under Earthquake Loadings

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Industrial plants are complex systems that need stringent requirements to ensure structural safety. If large amount of toxic or flammable materials are handled, the consequences of failures can affect wide surrounding areas.

The prediction and prevention of possible accidental scenarios triggered by the interaction of natural disaster with industrial equipment depend upon the reliability of available tools for structural design and hazard assessment. In this paper, attention is focused on industrial pipelines and on damages suffered by these structures under seismic sequences. Available data have been classified on the basis of seismological, geotechnical, structural and performance parameters, in order to assess the main factors affecting the seismic vulnerability of pipelines. An observational correlation between pipeline performance and relevant earthquake intensity measures for both transient and permanent deformations is derived. Moreover, compared to the available literature performance parameters based on a repair ratio, new fragility formulations have been built on the basis of the failure probability of pipelines. This circumstance provided some interesting remarks on the loss of containment, which has been largely demonstrated as the main issue for qualitative and quantitative risk assessment depending on relevant failure mechanisms.

1. Introduction

Industrial plants are key components of the economic and social system of any modern country. Among others, a primary requirement for the industrial plants and their fundamental sections consists of its structural safety, especially when large amount of toxic and flammable substances are stored or manipulated. The risks analysis taking into account the interaction among natural catastrophic events as earthquakes and industrial installation is becoming a key aspect of the design of new facilities and management and upgrading of existing ones (NaTech risks) (Young et al. 2004; Krausman et al., 2011).

Industrial plants are composed by of structures and elements: in order to evaluate the seismic vulnerability of the plant as a whole. Vulnerability evaluation of each component, including tanks, basins and pipelines (Fabbrocino et al, 2005; Campedel et al., 2008) is required. In the present paper, pipelines with industrial and civil destination, for the transportation of fluids (water, oils, gas and wastewater) have been analysed. These infrastructures are commonly addressed as lifelines and are dislocated on wide areas having, however, a predominant one-dimensional intrinsic structural development. It is worth noting that in the case of pipeline the seismic response is quite complex due to dynamic interactions involving three different components: i) the soil around the structure that offers a lateral confinement; ii) the structure itself, depending on geometric and material features; iii) the fluid inside with its specific properties. Hence, it is easy to recognise that an integrated multi-disciplinary approach for the study of the seismic behaviour of these structures is required. In the following sections the most relevant aspects of pipelines seismic vulnerability are discussed, highlighting the most important limitations. Based on the observation of pipelines damage occurred during past earthquakes, a collection of cases was previously selected in order to evaluate fragility curves able to fit requirements of common procedures for industrial risk assessment of critical facilities. Some aspects of the fragility and probit functions construction are also discussed.

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2. Tools for seismic Quantitative Risk Analysis of the industrial pipelines

Generally speaking a common tool for structural damage estimation is represented by the fragility curves. Specifically, the seismic damage of the structures is generally described through curves which relate the probability of exceedance of given performance depending on a properly selected seismic intensity measure. In the case of pipelines, a performance indicator for the pipeline damage due to the earthquake is, commonly represented by the Repair Rate, which gives the numbers of repairs for a unit length of pipeline. This is primarily due to the need to estimate costs of infrastructure repair associated to a seismic event. Pineda-Porras and Najafi (2010) discussed the most common fragility formulations for seismic damage estimation of pipelines: the intensity indicators for the seismic action are various and strictly dependent on the geotechnical aspects related to the pipeline damage. Moreover, the curves are empirical and based on post-earthquake pipeline damage data collection.

Based on experience and data collected during past earthquakes, the existing fragility curves could be divided in two categories (O'Rourke and Liu, 1999): 1) Strong Ground Shaking (SGS): the common effect is a deformation of the soil which surrounds the pipeline without breaks or ruptures in the soil; and 2) Ground Failure (GF): the surrounding soil is affected by failure phenomena caused by the earthquake.

Concerning the strong ground shaking effects, about 25 fragility formulations are available in literature with different seismic intensity indicators: PGA (Peak Ground Acceleration), PGV (Peak Ground Velocity), MMI (Modified Mercalli), PGV^2/PGA and PGD_1 (Peak Ground Displacement). In Figure 1, the frequency of each indicator was shown: most of the fragilities have PGV as the reference indicators.

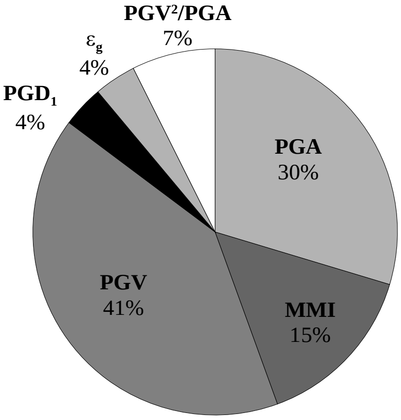

Figure 1: Percent frequency of SGS fragility curve on the basis of dose parameter.

Another important aspect of the analysis of existing seismic fragilities is the pipeline structural type. Therefore, Hazus (FEMA, 1999) implements the PGV algorithm of O'Rourke and Ayala (1993) for SGS, which gives the pipeline performance in terms of Repair Rate. It provides an approximated correlation between structural damage patterns (breaks or leaks) and geotechnical aspects (SGS or GF): the result is that most of SGS are related to leaks and most of the GF to breaks. Moreover, the pipelines are divided in brittle and ductile, on the basis of the seismic performance in terms of pre-failure deformations.

More in general, as for the structural aspects, the damage patterns occurred in the pipelines may be various and largely dependent on a number of features as the material properties and the joint detailing. Two significant categories for the seismic damage are therefore highlighted: 1) continuous pipelines (CP); 2) segmented pipeline (SP). Most of the existing fragility formulations are derived for segmented pipelines, because they all are generally based on data obtained from post-earthquake data of water and wastewater system (ALA 2001). Despite of these various aspects to be taken into account in the fragility formulations, existing curves are general power functions based on few data (Katayama et al. 1975, O'Rourke and Ayala 1993, Eidinger 1998), except the case of ALA (2001). Moreover, the Repair Rate may not be an objective parameter, because it depends on the reference length of pipeline, which is not uniform among the different formulations. Due to these limitations, it is easy to recognise that the risk assessment of pipelines, especially for industrial use, needs further development including: i) fragility formulations based on a performance indicator able to fit requirements of common procedures for industrial risk assessment, ii) specific levels of damage and specific curves for each type of geotechnical (SGS and GF) and iii) structural aspects (CP and SP). In such perspective, the investigation described in the next section is aimed at developing seismic fragility curves able to fit specific requirements of common Quantitative Risk Analysis methods.

3. Fragility derivation outline

The procedure employed was detailed in Lanzano et al. (2012). This is a general extension of the seismic damage estimation for aboveground tanks in a QRA as developed in Salzano et al. (2003; 2009). Similar procedures for the evaluation of seismic vulnerability of the geotechnical structures based on performance criteria were adopted by the PEER (Pacific Earthquake Engineering Research) and discussed by Kramer et al. (2009). In this work, the basic steps analysis are briefly retrieved: 1) observational data collection obtained mainly by post-earthquake reports, considering all the well-documented cases; 2) estimation of the seismic synthetic parameters for each collected data through the shaking maps, attenuation laws, measurements or data obtained from the post-earthquake reports; 3) check and validation of the collected data through models for the soil/pipeline interaction; 4) definition of an effective database throughout the classification of relevant classes depending on the pipeline type, damage state DS and risk states RS indicators; 5) statistical analyses of the data, test verifications and errors estimations; 6) fragility functions and probit analysis (Finney, 1971) for homogenous classes of pipelines. In this section some relevant aspects were highlighted: the classification criteria for damage and risk states are discussed; the verification of database on the basis of simplified analyses is explained. In particular, the analytical model to describe soil/structure interaction for continuous pipelines under strong ground shaking. In the next section, some results were given, in terms of fragility and probit curves and threshold values. These curves could be considered relevant for gas pipelines, which are mandatory continuous.

3.1 Damage states and risk states

The damage indicators of the Table 1 are properly recalibrated from the simplified classification taken from Hazus (FEMA, 1999), which considered only leaks and breaks; these classes correspond approximately to DS1 and DS2 of Table 1, which are better defined in each damage point, including an initial class of "no damage".

Table 1: Damage states for pipelines

States	Damage	Patterns
DS0	Slight	No damage; pipe buckling without losses; damage to the supports 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.

In order to correlate the pipelines damage with its consequences in conjunction with the damage states, other indicators of performance were defined, called "risk states". The risk states were characterized on the basis of the possible undesirable effects of pipeline damage on the environment; the indicator for the harmful effects was the amount of containment fluid loss. The risk states were organized in order to match the corresponding damage states (Table 3).

Table 2: Risk states for pipelines

States	Risk	Release of containment
RS0	Null	No loss of fluid
RS1	Low	Limited and time-distributed loss of fluid
RS2	High	Instantaneous large loss of fluid

In this way three risk states can be listed:

a. the RS0 corresponds to DS0, in which the damage type, even if severe, did not cause any loss of containment;
b. the RS1 was formulated in order to match DS1 class, where were inserted all the damage that cause the loss of a limited or time-distributed amount of fluid;
c. the RS2 has the highest level of risk and accounts all the damage in DS2, correlated to the release of large amount of fluid in a very short time interval.

These classification criteria were organized specifically for the pipelines used in the natural gas transport (continuous); therefore the classes must be recalibrated, when the water and wastewater systems are considered, because the limited or large release of water and gas has different effects on environment and same damage level should belong to different risk classes. Moreover the construction technologies for water and gas pipelines are generally different (SP vs. CP).

The accurate description of different risk states was performed in terms of containment loss, because this represents a key tool in Quantitative Risk Analysis. Therefore the effects estimation of accidents in the industrial plants related to NaTech risks as earthquakes was carried out on the basis of the treated material release, when it is flammable and pollutant (Salzano et al. 2003).

3.2 Database validation

A few indications are present in the current codes concerning the seismic behaviour of pipes. In particular, the Eurocode 8 part 4 (EN 1998-4, 2006) gives some general principles to ensure earthquake protection. Two types of pipelines are considered: aboveground pipelines and buried pipelines. For buried pipelines, the soil/structure interaction is always not negligible, whereas for the aboveground pipelines the geotechnical effects are related with the structure support loss and differential movements. In particular, the seismic design of underground structures under SGS is based on the prediction of the ground displacement field. The emphasis on displacement is in contrast with the design of surface structures, which focuses on inertial effects of the structures itself.

Simplified expressions for the evaluation of the surrounding ground deformation depending on the incident waves are available (Newmark, 1967); in particular maximum longitudinal deformation can be calculated as:

$$\varepsilon = \frac{PGV}{V_R} \tag{1}$$

in which PGV is the peak ground velocity and V_R is the apparent velocity of Rayleigh waves, which are the most significant waves, considering that pipelines are close to the soil surface. PGV is the seismic intensity parameters; instead, V_R is a measure of the stiffness of the soil layer, where the pipeline is placed. In one of the reports of the European Integrated Project LESSLOSS (2007), it has been observed that the most critical strain is the longitudinal deformation along the pipe. However, St. John and Zarah (1987) gave the simplified expression to evaluate seismic strain for different occurring wave and incidence angle.

Table 4 summarises all the most relevant aspects for continuous pipelines from the structural perspective and shows all the possible combinations of material and joints.

Table 3: Structural aspects in the seismic behaviour of continuous pipelines (CP)

Materials	Joints	Damage patterns
Steel; Polyethylene; Polyvinylchloride; Glass Fiber Reinforced Polymer.	Butt welded; Welded Slip; Chemical weld; Mechanical Joints; Special Joints	Tension/compression cracks; local buckling; beam buckling

The maximum strains provided by Equation (1) were compared with the limit deformation capacity (Hall and Newmark, 1977), accounting the different damage patterns, materials, joint type (see Table 3) for each investigated case, according to the Eurocode indications. The deformation capacity considered in the analysis of the damage cases is assumed to be equal both for tension and compression (4% for steel). It is a simplified approach, since it is well known that buckling deformation is a dependent upon the ratio t/R between thickness t and radius R. According to damage states and risk states of Tables 1 and 2, the tension breaks are associated to a large release of containment fluid and high risk state (RS2); instead the buckling cracks are relative to limited release of fluid (RS1).

4. Results

The collected data set is composed of approximately 400 samples. About 125 cases are relative to continuous pipelines under strong ground shaking (33%). The samples for the fragility curves construction come from 10 different earthquakes (Long Beach 1933, Kern County 1952, Kern County 1954, San Fernando 1971, Michoacan 1985, Whittier Narrows 1987, Erzincan 1992, Northridge 1994, L’Aquila 2009, Maule 2010). The complete analysis of the database was given in Lanzano et al. 2011.

4.1 Fragility curves

The database distribution was fitted using a cumulative log-normal distribution. The fragility curves for continuous pipelines under SGS are shown for $RS \geq RS1$ and $RS=RS2$ in Figure 2: the curves represent the probability of each possible damage induced by SGS in the CP in function of the value of PGV. In Table 3, the median μ and the shape parameter β of the distribution were given.

Table 4: Fragility coefficients for CP under SGS.

Risk state	Fragility	
	μ (cm/s)	β
RS≥RS1	45,22	0,39
RS=RS2	71,16	0,20

4.2 Thresholds

The seismic vulnerability of pipelines for Quantitative Risk Analysis has been estimated by using the classical probit analysis. The probit variable Y is expressed in the Equation (2), as a dose-response model: Y is the measure of a certain damage possibility in function of a variable "dose" V, which was the PGV in this specific case.

$$Y = k_1 + k_2 \ln V \tag{2}$$

The variable Y should be related to a probability of pipeline damage. The probit coefficients k_1 e k_2 are given in the Table 4. The probit functions were shown in Figure 2.

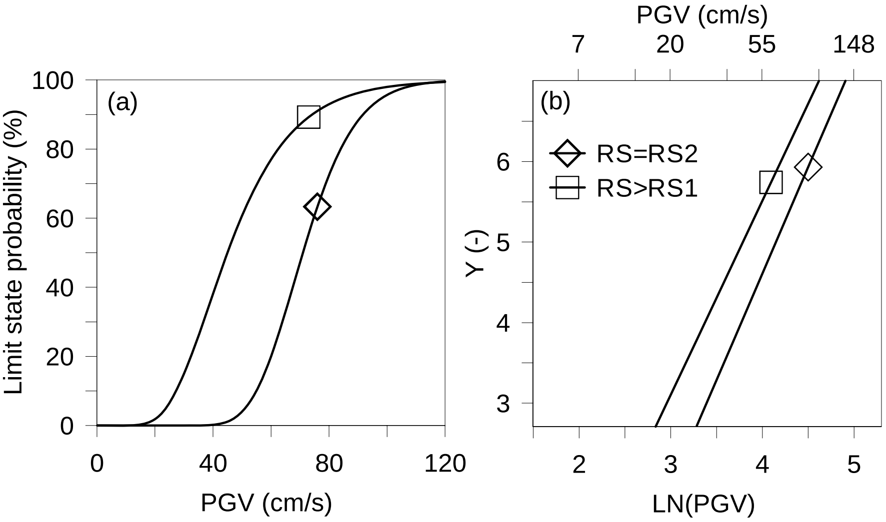

Figure 2: Fragility (a) and Probit functions (b) for continuous pipelines under SGS.

Cut-off threshold values of the PGV intensity measure parameters has been estimated and shown in Table 5: it corresponds to the PGV providing a value of the dose equal to 2.71 (zero probability). The difference in the threshold PGV values of ≥RS1 and RS2 is about 10cm/s.

Table 5: Probit coefficients for CP under SGS.

Risk state	Probit		Threshold PGV
	k_1	k_2	(cm/s)
RS≥RS1	-4,12	2,41	17,05
RS=RS2	-5,95	2,64	26,58

Conclusions

In this paper, an overview of a novel observational performance analysis of continuous pipelines is reported Seismic fragility curves were derived using a different performance indicator, compared with those available in existing technical literature. In particular, the selected indicator consists of the probability of failure related to a given damage level. Specific remarks were provided with reference to the classification of observed effects on the basis of reformulated damage states DS and risk states RS. Validations and results of the data set elaboration were discussed, with particular attention to continuous pipelines under strong ground shaking. The most interesting outcome of the work is represented by relevant damage threshold values that can be assumed as useful parameters for QRA analyses of Industrial Plants under NaTech events.

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