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An Observational Analysis of Seismic Vulnerability of Industrial Pipelines

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Industrial plants are complex systems that need stringent requirement for structural safety, as large amount of toxic and flammable materials are often handled and consequences of failures can affect wide surrounding areas. Prediction and prevention of possible accidental scenarios, triggered by the interaction of natural hazard such as earthquakes with industrial equipment depend upon the reliability of available tools for structural design and assessment. In this paper, attention is focussed on industrial pipelines and on damages suffered by such structures during recent earthquake sequences. Available data were classified on the basis of different correlated issues as seismological, geotechnical, structural and performance parameters, in order to assess the main factors affecting their seismic vulnerability. Results provided a preliminary correlation of pipeline performance and relevant earthquake intensity measures. Some remarks on the loss of containment, which has been largely demonstrated as the main issue for qualitative and quantitative risk assessment, in relation with relevant failure mechanisms, are also provided.

1. Introduction

A key aspect in the broad topic of the safety of industrial plants is their seismic vulnerability. In particular, large efforts are required to ensure the structural safety of the equipment when large amount of toxic and flammable substances are stored or manipulated. However, the seismic response of industrial structures was sometimes not satisfactory in some strong recent earthquakes, e.g. Northridge, California, 1994 (Lau et al., 1995) and L'Aquila, Italy, 2009 (Grimaz and Maiolo, 2010).
This circumstance strengthens the need to develop and enhance the engineering framework and to tackle all technical issues related to design and to the performance assessment of industrial structures. In particular, the concurrent action of different disciplines has to be recommended: the geotechnical engineering to study the soil/structure interaction during the seismic event; the structural engineering to study the construction technology and the damage mechanisms; the hydraulic engineering to evaluate eventual dynamic effects of the transported fluid; the industrial engineering to relate the damage with consequences and losses due to an eventual failure (QRA). Moreover, basic knowledge of seismological and geological settings is also needed, in order to estimate the seismic parameters and its degree of uncertainty. In the present paper, an observational analysis of earthquake damage is discussed with specific reference to pipelines. Preliminary fragility formulations for pipelines are also discussed as a sample outcome of the approach. The fragility formulation refers to pipelines and damages induced by strong motion shaking (SGS). A cut-off intensity measure obtained from a probit

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analysis - in terms of peak ground velocity (PGV) - is provided. Further work is needed to extend and validate such results, but some interesting aspects for risk evaluators can be certainly addressed.

2. Seismic vulnerability of pipelines

Pipelines are structural components widely used for the industrial and civil purposes. These structures are commonly addressed as lifelines and are dislocated on wide areas, having, however, a predominant one-dimensional intrinsic structural development. The pipelines are used for the transportation of fluids, as water, oils, gas and wastewater. A few indications are present in the current codes concerning the seismic behaviour of these structures. In particular, the Eurocode 8 part 4 (EN 1998-4, 2006) gives some general principles to ensure earthquake protection. The main prescriptions could be summarized as:

1) Each structure must be verified for ultimate limit state; two damage limitation states need to be satisfied: full integrity and minimum operating level;
2) The reference seismic action has to be selected depending on the relevance and the use of the structure; this means that the high the relevance of the structure, the lower is the probability of exceedance of the seismic intensity measure, in the reference time interval of 50 years. Italian code provides a higher reference time interval for the industrial structure (NTC, 2008) varying from 75 up to 200 years;
3) Two types of pipelines are considered in the codes: aboveground pipelines and buried pipelines; for buried pipelines, the soil/structure interaction is always not negligible; for the aboveground pipelines the geotechnical effects are related with the structure support loss and differential movements;
4) The hydraulic dynamic effects are considered negligible, due to the filling level inside the pipelines, except for the cases of wastewater system;
5) The use of continuous pipelines for systems which treat flammable and pollutant material is mandatory; the codes, in this case, indicate approximately the values of the limit strains for the construction materials;

It easy to recognise that an integrated multi-disciplinary approach for the study of the seismic behaviour of these structures is generally required. Based on experience and data collected during past earthquakes, geotechnical dynamic effects related to the 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 (GF_1), liquefaction (GF_2) and landslides induced by the shaking (GF_3). Clearly these seismic failure mechanisms could appear only in specific geotechnical conditions, then these are site dependent (i.e., for the loose sands under groundwater level for the GF_2 phenomenon).

As for the structural aspects, damage patterns occurred in the pipelines are various and largely dependent by a number of features of the structures, as the material base properties and the joint detailing. Table 1 summarises all the most relevant aspects from the structural perspective and shows all the possible combinations of material and joints.

Table 1: Structural aspects in the seismic behaviour of pipelines

Pipelines	Materials	Joints	Damage patterns
Continuous (CP)	Steel; Polyethylene; Polyvinylchloride; Glass Fiber Reinforced Polymer.	Butt welded; Welded Slip; Chemical weld; Mechanical Joints; Special Joints	Tension cracks (Figure 1a); Local Buckling (Figure 1b); Beam buckling (Figure 1c)
Segmented (SP)	Asbestos Cement; Precast Reinforced Concrete/Reinforced Concrete; Polyvinylchloride; Vitrified Clay; Cast Iron; Ductile Iron.	Caulked Joints; Bell end and Spigot Joints; Seismic Joints	Axial Pull-out (Figure 1d); Crushing of Bell end and Spigot Joints (Figure 1e); Circumferential Flexural Failure and Joint Rotation (Figure 1f).

Two significant categories for the seismic damage are therefore highlighted: 1) continuous pipelines (CP); 2) segmented pipeline (SP). It is worth noting that a similar approach has been already adopted in the context of Hazus (FEMA, 1999), where the pipelines are divided in brittle (SP) and ductile (CP), on the basis of the seismic performance in terms of pre-failure deformations. Considering the specific features of the segmented pipelines, the Table 1 showed that the damage point was almost always at joint location.

3. Overview of the existing fragility formulations

The most common tools for the estimation of the damage are the fragility curves. The seismic damages of the pipelines are generally described through curves in which a performance indicator is expressed as a function of a seismic intensity measure. The performance indicator for the pipeline damage due to the earthquake generally is the repair rate, which gives the numbers of repairs for a unit length of pipeline. The intensity indicators for the seismic action are various and strictly depended on the geotechnical aspects related to the pipeline damage. Pineda-Porras and Najafi (2010) discussed the most common fragility formulations for seismic damage estimation of pipelines. At the moment, the existing fragility curves could be divided in two categories: SGS: 25 fragility formulations with seismic intensity indicators PGA (Peak Ground Acceleration), PGV (Peak Ground Velocity), MMI (Modified Mercalli), PGV^2/PGA and PGD_1 (Peak Ground Displacement); GF: 7 fragility formulations with seismic intensity indicators PGD_2 (Permanent Ground Displacement). Hazus (FEMA, 1999) gives an approximated correlation between 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, 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 system (ALA, 2001). Due to these limitations, it is easy to recognise that risk assessment of industrial facilities needs further development and fragility formulations based on different performance indicators, specific levels of damage and specific curves for each type of geotechnical (SGS and GF) and structural aspects (CP and SP). In such a perspective, the investigation described in the next section is aimed at developing seismic fragility curves able to fit specific requirements of common QRA methods.

4. Investigation and analysis procedure

The procedure employed here is a general extension of the seismic damage estimation for aboveground tanks in a Quantitative Risk Analysis (QRA) as developed in Salzano et al. (2003). 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 analysis steps are:

1. Observational data collection obtained by post-earthquake reports and technical literature, considering all the well-documented cases, particularly in terms of location, material, joint, geotechnical aspect and damage pattern;
2. Estimation of the seismic parameters for each collected data through the damage location from: a) shaking maps (USGS); b) attenuation laws (specific for the investigated area); c) data obtained from accelerometers measurements (PGA, PGV, PGD_1); d) data obtained from the post-earthquake reconnaissance (PGD_2);
3. Check and validation of the collected data through models for the soil/pipeline interaction, variable for pipeline type (CP and SP) and geotechnical mechanism (SGS and GF);
4. Creation of thoughtful database founded on classification in significant classes for various pipelines types (according to § 3) and according damage state DS indicators (Table 2);
5. Statistical analyses of the data, test verifications and errors estimations;
6. Fragility functions and probit analysis (Finney, 1971) for homogenous classes of pipelines (Salzano et al., 2003).

The damage indicators DS of the Table 2 are properly recalibrated from the simplified classification of Hazus (FEMA, 1999), which considered only leaks and breaks; these classes correspond approximately to DS1 and DS2 of Table 2, which are better defined in each damage point, including an initial class of “no damage”. Based on the complete database and on the observed behavior of pipelines, five possible classes of fragility curves could be recognized: a) buried CP under SGS; b) buried CP under GF; c) buried SP under SGS; d) buried SP under GF; e) aboveground pipelines (AP). In the following preliminary fragility and probit functions were obtained for a specific class of pipelines (a): the data were relative to continuous pipelines (which are a typical class for gas pipelines) under strong ground shaking (SGS).

Table 2: Damage states for pipelines

States	Damage	Patterns
DS0	Slight	Investigated sections with 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.

5. SGS fragility curve for gas pipelines

The collected data set is composed of approximately 400 samples, coming from about 300 edited books, papers and post-earthquake reports. The investigated earthquakes were around 40, even if only 22 should be considered as significant for the pipeline damages, from 1906 to 2010. Additional information on the database are reported elsewhere (Lanzano et al., 2011).

5.1 Verification of the database

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 to the design of surface structures, which focuses on inertial effects of the structures itself. The behaviour of a continuous pipeline under SGS is usually approximated to that of an elastic beam subjected to deformations imposed by surrounding ground. Three types of deformations characterise the response of underground structures to seismic motions (Owen and Scholl, 1981):

- *axial deformations* generated by the components of seismic waves aligned to the axis of the pipe, causing alternate compression and tension;
- *bending deformations* caused by the components of seismic waves producing particle motions perpendicular to the pipe axis;
- *ovaling or racking deformations* developing when shear waves propagate normally, or nearly, to the pipe axis, resulting in a distortion of the cross-sectional shape of the lining (Lanzano, 2009).

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:

$$\varepsilon = \frac{PGV}{V_R} \qquad (1)$$

in which PGV is the peak ground velocity and V_R is the apparent velocity of Rayleigh waves, which is the most significant waves, considering that pipelines are close to the soil surface. The maximum strains evaluated using the Equation (1) were compared with the limit deformation, accounting the different damage patterns, materials, joint type for each investigated case (Hall and Newmark, 1977). The entire database was checked, examining the possibility that the damage were likely.

5.2 Preliminary Fragility curve and probit function

The seismic vulnerability of pipelines 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, based on a log-normal distribution of the data set for fragility estimation. A preliminary fragility curve and the related probit function for continuous pipelines under SGS shown in Figure 1, considering all the collected case with DS≥DS1: the curves represent the probability of every 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, together with the probit coefficients k_1 e k_2. A preliminary cut-off value of the PGV intensity measure parameters has been estimated. It corresponds to the PGV providing a value of the dose equal to 2.71 (zero probability) and is about 23 cm/s.

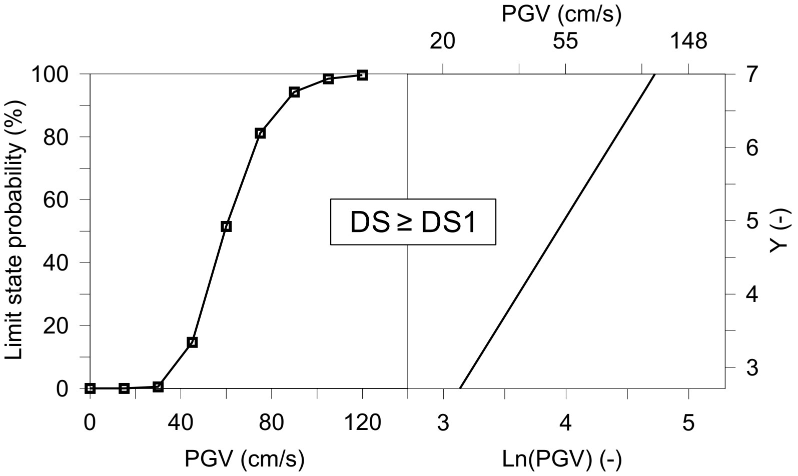

Figure 1: Preliminary fragility (left) and probit (right) function for continuous pipelines under SGS.

Table 3: Preliminary fragility and probit coefficients for CP under SGS.

Damage state	Fragility		Probit	
	μ (cm/s)	β	k_1	k_2
≥DS1	59.4	0.26	-5.75	2.7

Conclusions

The paper provides a preliminary fragility and probit formulations for continuous pipelines (commonly steel and plastic pipes for gas transportation) under strong ground shaking (loading due to surrounding soil deformation induced by the waves passage). The approach - differently from formulation of available fragility curves, based on the “repair rate” as a performance indicator – is in the line with similar works focused on steel tanks. In this work, each observational data was classified according to a specific damage state (table 2) and statistically treated using, as a “dose” parameter, the peak ground acceleration (PGV). For future developments, other fragility formulations are under development also for segmented pipelines (SP) and ground failure (GF) conditions.

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