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Vulnerability of Pipelines Subjected to Permanent Deformation Due to Geotechnical Co-seismic Effects

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Pipelines are basilar structures for the development of civil and industrial activities. Their seismic behaviour could be analyzed by applying a multi-disciplinary approach. In particular, for underground pipelines, soil/structure interaction is considered determinant during the seismic event. Moreover, for specific site conditions, ground failure phenomena induced by earthquakes might occur. Since such phenomena are generally associated to permanent soil displacement, the related deformations could be not tolerated by the pipelines, causing structural breaks and/or the losses of fluid containment.
On the basis of a large collection of damage occurred to pipelines during recent earthquakes, a class of fragility curves was built up for underground structures underground failure. These curves were given as the probability of the occurrence of certain damage in a pipeline segment as a function of a seismic parameter. Therefore, compared to the existing formulations based on the estimation of a repair rate, RR, this study gives fragility curves which are directly useable on HAZUS-like platform, similarly to punctual structures, as aboveground tanks. These empirical formulations could be easily treated in order to obtain tools for the estimation of seismic vulnerability, implemented in numerical codes for QRA (Quantitative Risk Analyses) of industrial plants. For this purpose, in this paper, the probit parameters and the threshold values are also given.

1. Introduction

Industrial plants are very complex structures, consisting in several different types of separate structures and components. In order to ensure the safety and the operation of the entire industrial plant against extreme natural or accidental events, some tools are necessary to perform risk analyses.
The Na-Tech events include the catastrophic natural events, as earthquakes, tsunami, flood and hurricane, which can cause a severe damage to industrial structures, causing the release of hazardous fluids with serious impact on social, economic and environmental context (Krausmann et al 2011).
Among the natural hazards, the seismic action was widely studied, especially concerning industrial topics in order to give methodologies and tools for Quantitative Risk Analysis (Fabbrocino et al., 2005; Campedel et al. 2008; Salzano et al., 2009). These tools are generally summarized into fragility curves, which give the probability of damage based on a significant intensity parameters, or threshold values of the seismic intensity.
In this paper, fragility curves were constructed for pipelines, which are crucial components for the operation of the common industrial plants. On the basis of a wide database of damage cases, fragilities and thresholds were evaluated considering, as a likelihood damaging effect, the permanent displacement induced by co-seismic ground failure phenomena.

2. Seismic performance of the pipelines

During some of the last earthquakes, several pipelines suffered severe damages, which, in some cases, caused harmful consequences because of the release of hazardous materials in the environment. The

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example of Balboa Blvd., during the Northridge earthquake (1994) in California, is considered meaningful, because of the permanent displacement induced by a liquefaction of a loose sand layer (O'Rourke & Palmer, 1996). Some natural gas pipelines were severely damaged by tension and compression strains; moreover the instantaneous leak of containment fluid caused a large explosion in the Northridge town and several deaths.

The main relevant references, which were accounted in this paper for pipelines design and risk analyses, are the Eurocode 8 part 4 (EN 1998-4, 2006), which gave few prescriptions for seismic analyses of pipelines; and the technical manual of HAZUS (FEMA, 2004), which is GIS-based software for loss estimation due to natural hazards, as earthquake. For the industrial structures, more specific tools should be given, which could be implemented in dedicated software for QRA (Girgin and Krausmann, 2012).

From a structural point of view, the current technology in pipeline construction could be divided in two main groups:

- Continuous pipelines (CP): steel and plastic pipelines, with welded or mechanical joints; these pipelines are mainly used for transportation of dangerous fluids, because of the high strength and ductility;
- Segmented pipelines (SP): concrete and brittle iron pipelines, with caulked and bell and spigot joints; these pipelines are used for water and wastewater systems.

These two categories could approximately match the HAZUS pipeline division in brittle (SP) and ductile (CP). Therefore, these two categories are significant for seismic response of pipelines, because the different damage patterns, which are related to the different restoring strength of the joints, compared to pipeline body.

Starting from a large collected database of pipeline damages after strong earthquakes (more details in Lanzano et al. 2013a), the most important classification criterion concerned the damage severity (DS), which is listed in Table 1. This procedure was commonly performed for the construction of fragility curves for aboveground and concentrated structures. In HAZUS, as a matter of fact, the indexes for pipeline damage classification are very basic: two damage levels are considered, leaks and breaks, mixing up the effects and the damage itself. In Table 1, these performance based indexes were recalibrated, accounting for the different behaviour of segmented and continuous pipelines (Lanzano et al. 2012).

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.

Another important topic for seismic performance of pipelines (and for damage classification) is the interaction with soil, which, especially for buried pipelines, is always not negligible. O'Rourke and Liu (1999) described two different mechanisms of soil/structure interaction: strong ground shaking (SGS), which produces transient strains of soil because of the seismic travelling wave passage; ground failure (GF), due to different co-seismic phenomena, which causes permanent deformations. In this paper, the work is focused on the response of pipelines under permanent deformations, whereas transient deformations are subject of previous work (Lanzano et al. 2012).

3. Ground failure phenomena

According to O'Rourke and Liu (1999), the most important failure mechanisms related to pipeline damage induced by earthquakes are:

- GF1: Active Fault; it is a discontinuity between two parts of the earth's crust, which suffered a relative displacement during an earthquake. The movement is concentrated in very confined areas;
- GF2: Lateral spreading; it is an almost horizontal movement, which occurs when a loose sand saturated deposit suffers liquefaction due to seismic shaking;
- GF3: Seismic subsidence; these phenomena are generally caused by the densification of dry sand, the consolidation of the clay or by the liquefied soil. The settlement induced by liquefaction is more frequent compared to the other ones, with larger deformations and higher damage to the structures;

- GF4: Earthquake-induced landslides; a large variety of phenomena, divided on the basis of material, movement type and other specific features, are included in this definition.

From a quantitative point of view, the severity of ground failure phenomena could be represented by the magnitude of induced permanent ground displacement, δ. Because of the different characteristics of the above listed phenomena, different empirical or analytical relations could be used for estimation of the maximum expected displacement. Some relevant empirical correlations are reported in Table 1.

Table 2: Empirical correlation for permanent displacement δ evaluation (δ=permanent ground displacement; M_w= moment magnitude; R_{ep}= epicentral distance; Y(or S)= slope inclination; PGA= peak ground acceleration; T_{15}= thickness of liquefiable soil layer; N= SPT blowcount; a_c= critical acceleration).

Ground Failure		Correlation	Parameters	Reference
GF1	Active fault	$\log\delta = -4.8 + 0.69M_w$	M_w	Wells & Coppersmith, 1994
GF2	Lateral spread	$\log(\delta_h + 0.01) = -7.28 + 1.017M_w$ $- 0.278\log R_{ep} - 0.026R + 0.497\log Y$ $+ 0.454\log S + 0.558\log T_{15}$	M_w, R_{ep}	Bardet et al., 2000
GF3	Subsidence	$\delta = 0.3H_1\dfrac{PGA}{N} + 2$	PGA	Takada and Tanabe, 1988
GF4	Landslide	$\log\delta = 2.3 - 3.3\dfrac{PGA}{a_c}$	PGA	Ambraseys and Menu, 1988

Using the correlations of Table 2, the permanent ground displacement was estimated for each collected pipeline damage case, on the basis of the seismological (M_w, R_{ep}, PGA), geometrical (Y, S) and geotechnical (T_{15}, N, a_c) input parameters. The soil parameters could be obtained from the standard in situ tests (T_{15}, N) or from simplified modelling of the seismic failure mechanism (a_c). In some cases, an in-field measurement of the permanent displacement was available and was compared to the estimated value in Figure 1a: a good agreement between measured and calculated displacement values, which has been divided per GF type, could be observed.

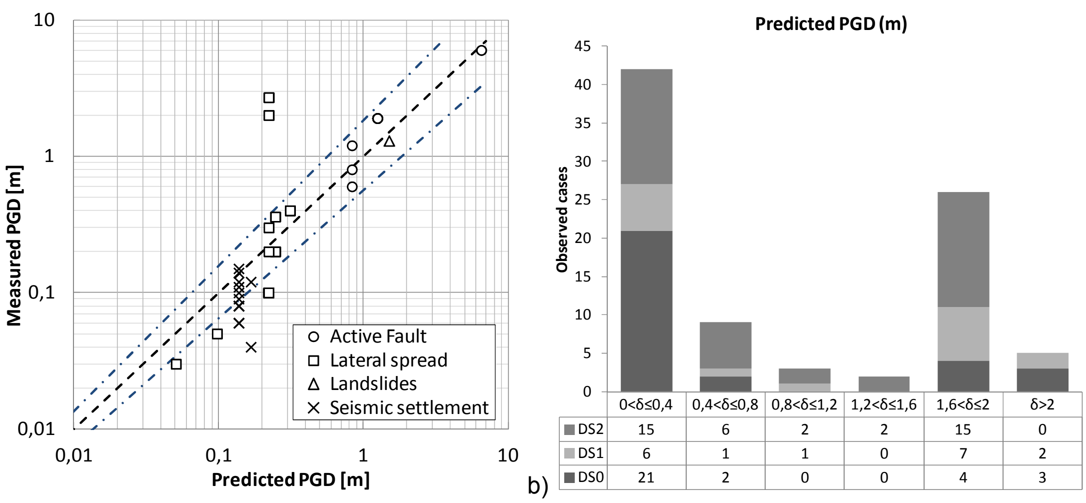

Figure 1: a) Comparison between predicted and measured values of PGD (Permanent Ground Displacement); b)Histogram plot of the observed cases on the basis of DS and PGD values.

The damage cases were also plotted in Figure 1b, as histogram based on increasing value of δ. The observed distribution is not unimodal: this is mainly due to the different maximum strain levels reached among the different ground failure mechanisms. As a matter of fact, the deformations induced by liquefaction are in the range of centimetres and decimetres; the values for active faults and landslides are in the range of meters. This observation has been accounted in the next construction of fragility curves.

3.1 Overview of fragility estimation for permanent deformations

The existing fragility correlations are based on the repair rate, RR, i.e. the number of repairs for a given pipeline length. Almost all the empirical correlations are based on the expression:

$$\mathrm{RR}\left(\mathrm{n^{\circ}repairs/km}\right)=\mathrm{a}\cdot\mathrm{PGD}^{\mathrm{b}} \quad (1)$$

These fragility curves are essentially based on Permanent Ground Displacement, PGD, induced by the co-seismic GF phenomena and are listed in Table 3.

Table 3: Main significant Ground Failure fragility correlations based on repair rate RR (S: steel; DI: ductile iron; CI: cast iron; AC: asbestos cement; C: concrete; WJ: welded joints; FJ: flange joints; CJ: caulked joints; D: diameter).

a		b	Reference
CP	SP		
2.18	7.82	0.56	Honegger and Eguchi, 1992
3.55 (S-WJ) 16.57 (S-FJ) 7.10 (DI-FJ)	23.67 (CI-CJ, AC-CJ) 16.57 (CI-FJ) 18.94 (AC-FJ, C-WJ) 23.67 (C-CJ)	0.53	Eidinger and Avila,1999
1.68 (S-WJ) 7.85 (S-FJ) 5.61 (DI-FJ)	11.22 (CI-CJ, AC-CJ) 8.98 (CI-FJ, AC-FJ) 6.73 (C, WJ) 11.22 (C, CJ) 7.85 (C, FJ)	0.32	ALA, 2001

The empirical formulation for Ground Failure proposed by Hoenegger and Eguchi (1991) has been also adopted by HAZUS. In order to implement these correlations for risk analyses in HAZUS, the expression should be then given in terms of damage probability, using a Poisson distribution. In the next sections different fragility tools are proposed, which are directly related to the consequences of loss containment, with particular reference to hazardousness of the released fluids.

4. Fragility and probit estimation

4.1 Methodology of analysis

The damage classes of Table 1 were reorganized with the scope of a definition of Risk States (RS). Similar approach was already carried out for the vulnerability assessment of aboveground tanks (Salzano et al. 2003) and already applied for natural gas (Lanzano et al. 2013b) and more in general industrial pipelines (Lanzano et al. 2013c). The RS are essentially based on the amount of released fluid; the class of risk was also divided considering the fluid type according to Table 4. An equivalent diameter Φ of the crack in the pipelines has been introduced as classification criterion.

Table 4: Risk States RS for pipelines (Φ = equivalent diameter).

States	Hazard	Patterns (loss of containment)	
		Gas/Vapour/Liquefied Gas	Liquid
RS0	Null	No losses	Limited loss
RS1	Low	Very limited losses: - Toxic (Φ < 1 mm/m) - Flammable (Φ < 10 mm/m)	Limited, time-distributed loss of hazardous substance: multiple losses (Φ < 10 mm/m)
RS2	High	Non- negligible losses	Large loss (e.g. entire tube surface) or multiple losses (Φ > 10 mm/m)

In most of the cases the Risk States matched the corresponding Damage States, but, in the cases of not hazardous liquids, a very limited amount of released fluid has been accepted also for RS0 class.

4.2 Fragility curves based on fluid losses

The historical data was ordered and divided in classes, based on increasing intensity measures values, in order to obtain approximately a uni-modal distribution. The experimental data were fitted using a cumulative log-normal distribution:

$$P(RS \geq RS_i) = \frac{1}{2}\left[1 + \mathrm{erf}\left(\frac{\ln PGA - \ln \mu}{\beta\sqrt{2}}\right)\right] \quad (2)$$

where μ and β are the median value and the of the distribution respectively. The fragility is expressed in terms of PGA. Therefore, starting from the comment to Figure 1b, most of the empirical expressions of Table 2, used for evaluation of permanent displacement, are based on PGA or similar parameters, which could be related to PGA through Ground Motion Prediction Equations (GMPE). The results of fragility estimation were then expressed in terms of probit parameters according to the expression:

$$Y = k_1 + k_2 \ln PGA \quad (3)$$

where Y is the probability of damage and k_2 and k_1 are the slope and the intercept of that straight line in the plane ln(PGA) - Y. According to probit analysis, a cut-off value could be evaluated, which corresponds to a failure probability practically zero. The results of this analysis were reported in Table 5 and Figure 2, with particular reference to RS2 class, including fragility, probit and threshold parameters.

Table 5: Fragility and probit coefficients for pipelines under GF.

Structural Aspects	Class Risk state, RS	Fragility μ (g)	β	Probit k1	k2	Threshold (g)
CP	≥ RS1	0.58	0.17	-	-	-
CP	= RS2	0.56	0.18	6.97	2.54	0.20
SP	≥ RS1	0.37	0.23	-	-	-
SP	= RS2	0.37	0.19	7.79	2.59	0.14

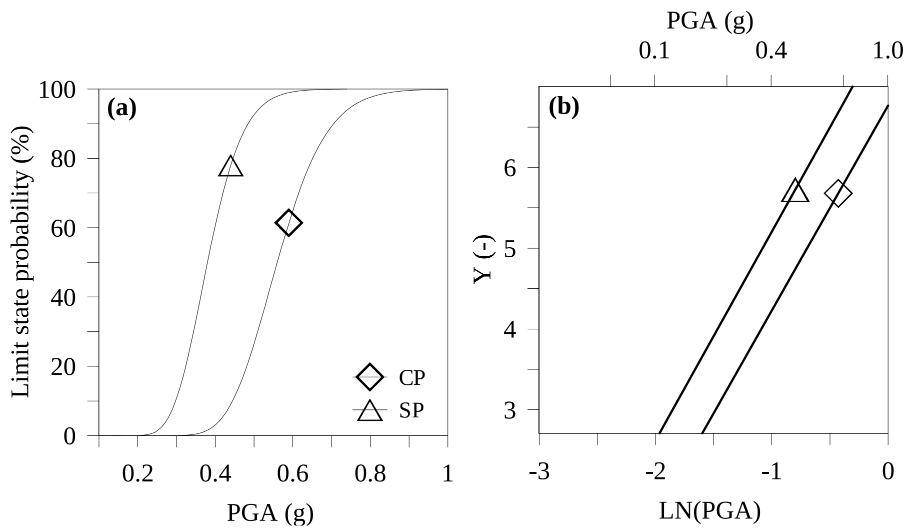

Figure 2: Fragility (a) and Probit (b) curves for RS=RS2

The estimated parameters are significant only for high risks (RS2), because the low risk cases are not reliable for statistical evaluation. Considering the scarcity of RS1 dataset, a possible reason could be investigated starting from the observation of HAZUS, where most (80 %) of the breaks (RS2) are related to permanent deformations.

5. Conclusions

In this paper, fragility curves for buried pipelines which undergo seismic permanent deformations are given. Thresholds seismic parameters for high risk conditions were also obtained. The curves were created by using a consistent database of pipeline damage cases, collected “ad hoc” for fragility estimation. The probability of failure was given on the basis of peak ground acceleration, which is a seismic synthetic parameter, also used for design and verification of the building, and commonly provided by the National Authorities. Fragility curves could be employed for quantitative risk analyses of industrial plants.

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