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Seismic vulnerability of gas and liquid buried pipelines

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ABSTRACT

Lifelines play a crucial and essential role in human life and in economic development. The resilience of those systems under extreme events as earthquakes is a primary requirement, especially when large amount of toxic and flammable material are transported.

In this work, the seismic vulnerability of buried gas and liquid pipelines has been analyzed, starting from a large number of damage data to pipelines collected from post-earthquake reconnaissance reports.

Seismic fragility formulations and threshold values for the earthquake intensity with respect to the release of content from different types of pipelines have been derived. The main outcome of the work is therefore a novel seismic assessment tool which is able to cover the needs of industrial risk assessment procedures and land use planning requirements.

1. Introduction

A primary requirement for the industrial installations and their fundamental components is the adequate structural safety level with respect to natural hazard and particularly to earthquakes, especially when large amount of toxic and flammable substances are stored or manipulated. Among the very large number of structural and non-structural components of the industrial plants, the pipeline system needs special attention. Indeed, the multiple interactions among the soil, the structure itself and the contained fluid during seismic events is not negligible for this class of structures. Therefore, in addition to the structural earthquake engineering, the key contribution of geotechnical and hydraulic engineering is required and a multidisciplinary effort is recommended.

In the past, pipelines have shown to suffer heavy damages when loaded by seismic actions, as in the recurrent and catastrophic earthquakes of California (San Francisco, 1906; earthquake of San Fernando, 1971; Northridge, 1994) and Japan (Kobe, 1995). However, despite the evolution in the anti-seismic techniques and the progress in the seismic design, relevant damages to pipelines have been still observed during recent earthquakes occurred in Italy (earthquake of L'Aquila, 2009; earthquake of Emilia, 2012), New Zealand (Darfield, 2010), Chile (2010), Japan (Tohoku, 2011).

Pipelines are frequently buried for two main reasons: first, the landfill protects the pipeline from above ground damaging events, either natural or anthropical. Moreover, the lateral confinement given by the surrounding soil, which increases with depth, mitigates the inertial seismic effects.

The present paper reports fragility curves, probit functions and threshold values for the structural damage of buried pipelines containing gases or liquids as function of a basic parameter of the earthquake motion. The data and the function can be profitably used in existing tool for the Quantitative Risk Analyses (QRA) which includes natural-technological risks (Na-Tech issue) (Campedel, Cozzani, Garcia-Agreda, & Salzano, 2008; Fabbrocino, Iervolino, Orlando, & Salzano, 2005), in Land Use Planning methodologies and more in general for the procedures activated by the public awareness with respect to the risks related to the transportation, transmission and distribution of hazardous substances, when loaded by natural events (seismic Na-Tech accidents (Krausmann, Cozzani, Salzano, & Renni, 2011; Salzano et al., 2013)).

1.1. Earthquake intensity measure

The first important aspect related to the seismic response of civil and industrial constructions is the proper measurement of the shaking level at the site of interest. Before quantitative seismology was developed, the seismic intensity was estimated only on the basis of the destructive effects on built environment and people perceptions. That led to observational scales as the Modified

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Table 1
Structural aspects in the seismic behavior of pipelines.

Pipelines	Use	Materials	Joints	Damage pattern
Continuous (CP)	Natural gas	Steel	Welded joints	Tension cracks
	Oil	Polyethylene (HDPE)	Mechanical or flange joints	Compression cracks
	Petroleum	Polyvinyl chloride (PVC)	Special seismic joints	Local buckling
	Water	Ductile iron		Beam buckling
Segmented (SP)	Water	Asbestos cement	Caulked joints	Axial pull-out
	Wastewater	Reinforced Concrete	Bell end	Crushing of bell end
		Polyvinyl chloride (PVC)	Spigot joints.	Crushing of spigot joints
		Vitrified clay		Circumferential failure
		Cast iron		Flexural failure.

Mercalli one (MMI or Macroseismic Intensity), that is still used nowadays for its practical implications. Actually, governmental agencies give the Macro-seismic Intensity maps for many historical and recent earthquakes. On the basis of historical data only, many empirical relations, developed to describe the performance of the structures during the earthquakes, were expressed as a function of MMI. This applies also to the seismic vulnerability of pipelines [Eguchi, 1991; O'Rourke, Toprak, & Sano, 1998]. More recently, instead, the deployment of seismic stations in seismic areas has led to the more common use of basic parameters obtained from the field measurements.

The most significant seismic instrumental parameters for structural applications are the Peak Ground Acceleration (PGA) and the Peak Ground Velocity (PGV), which are respectively the peak of the horizontal acceleration and velocity time history obtained from accelerometer measurements. Quite clearly, these parameters are only concise descriptions of the seismic motion and do not give a complete information of the local ground motion, in terms of frequency content and signal duration, which are important parameter for the structural response. Despite of these limitations, due to their simplicity, the above cited parameters are currently the most used indexes in order to relate structural damage and seismic intensity, including pipelines, and will be used in this work.

1.2. Seismic behavior of pipelines

Pipelines for the transportation of fluids are widely used for industrial and civil purposes. These structures, having a predominant one-dimensional development, are commonly addressed as lifelines and are often dislocated over wide areas. Few and only general provisions are given in the current relevant codes concerning the seismic behavior of these structures. In particular, the Eurocode 8 part 4 (EN 1998-4, 2006) provides only general principles to ensure earthquake protection. The most relevant prescriptions in the context of the present paper may be summarized as follows:

i) each structure, including pipelines, tanks and silos, must be verified for ultimate limit state;
ii) at least one of two damage limitation states needs to be satisfied: full integrity and minimum operating level. In the latter case, a certain level of damage is allowed, on the basis of a possible loss consequences of fluid or functionality;
iii) the principal safety hazard directly associated with the pipeline rupture under a seismic event is related to explosions and fires, particularly with regard to gas pipelines. The distance of the location and the size of the population that is

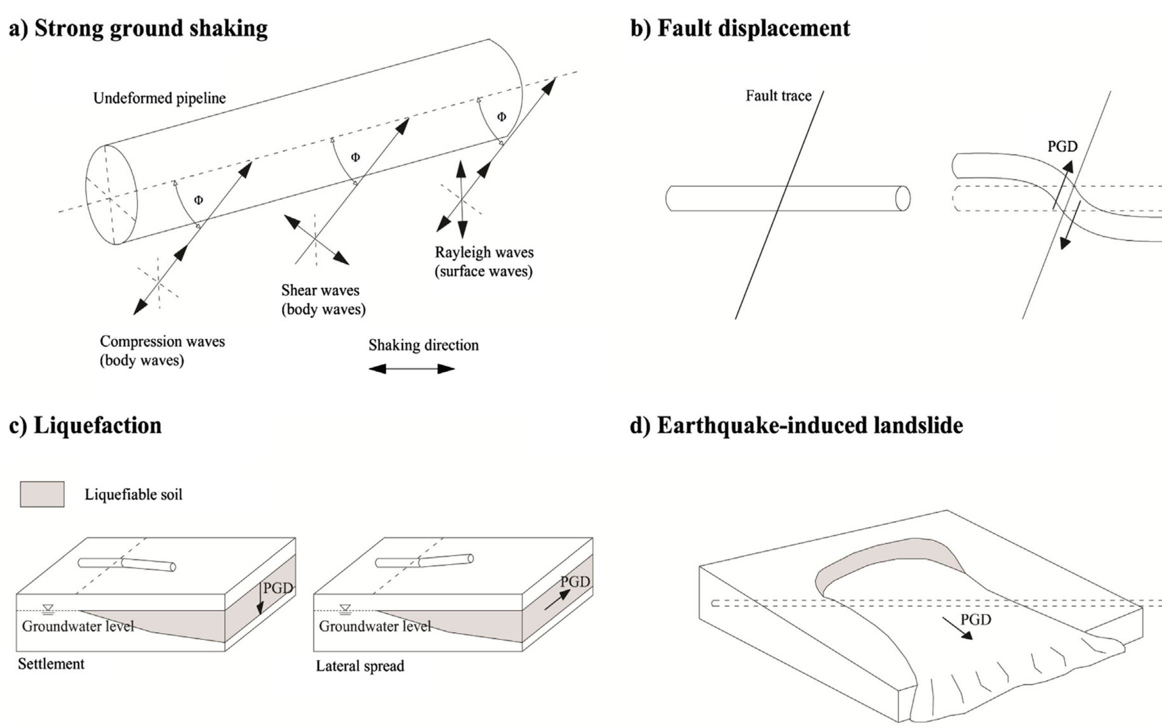

Fig. 1. Summary of strong ground shaking and ground failure interaction mechanisms (adapted after O'Rourke & Liu, 1999).