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Integrated approach to the seismic vulnerability assessment of industrial underground equipment and pipelines

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ABSTRACT Severe requirements for the safety of industrial equipment are necessary when large amount of toxic and flammable materials are handled. Among others, structural reliability of infrastructures for storage and transportation may result as an effective prevention and mitigation measure of effects related to accidental scenario induced by natural hazard such as earthquakes. This is the background of a multi-disciplinary study on the assessment of seismic vulnerability of selected industrial equipment, like the pipelines, underground tanks and buried basins, whose main aspects are herein summarized. In this paper, a collection of data concerning the damages induced by earthquakes on pipelines was carried out. The main objective is the construction of a database, in view of the development of observational fragility curves depending on the specific pipelines type, in order to provide simplified tools for industrial quantitative risk analysis.

Key words: industrial equipments, pipelines, risk analysis.

1. Introduction

Industrial plants are key components of the economic and social system of a modern country. 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. Among others, the analysis of risks related to the interaction between natural catastrophic events such as earthquakes and industrial installation is becoming a basilar topic in the design of these structures (NaTech risks) (Salzano *et al.*, 2009; Krausmann *et al.*, 2011).

Industrial plants are composed by a system of structures and elements: in order to evaluate the seismic vulnerability of the whole plant, it is necessary the evaluation of the vulnerability of each component, including tanks, basins and pipelines. In this study, a class of these structures is considered; Table 1 reports the analyzed components and their characteristics. It is worth noting that the seismic response is, in all cases, 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.

In this paper the main relevant aspects of seismic vulnerability of the pipelines are discussed.

Table 1 - Some features of the industrial components investigated.

Lifeline	Use	Materials
Pipelines	Transport and distribution of gas and liquids for civil and industrial purposes	Steel, plastic materials, concrete
Underground horizontal tanks	Storage of GPL fuel	Steel (prefabricated)
Buried and semi-buried basins	Treatment of residual and pollutant liquids	Concrete

On the basis of the observation of damage to pipelines occurred during the past earthquakes, a collection of cases was selected, in order to highlight common features and differences.

The database discussed in this paper exhibits a large potential as a basic tool to develop reliable fragility curves for different kind of lifelines to be used in the context of Na-Tech risk assessments.

2. Observation of the seismic damages occurred to the industrial plants

In the last decades, the damages caused by the earthquakes were collected and registered through the direct observations and the analyses of the consequences of the event. Many papers and reports were published (see for example www.geerassociation.org, www.earthquakespectra.org), describing the main features of the seismic event and the consequence in terms of structural damage and social and economic impact (Fabbrocino *et al.*, 2005; Jaiswal and Wald, 2013). Concerning the industrial plants, well-documented post-earthquake reports were written down after major seismic events, starting from San Francisco (1906) till recent Tohoku (2011) earthquakes. The better-documented data are mostly available for the stronger and most recent earthquakes, like, for instance, the Northridge earthquake (Lau *et al.*, 1995), in which many components and equipment of the industrial plants severely failed. Similar considerations are valid also for Italian seismic events: in the most recent strong motion earthquakes in Italy, L'Aquila (2009) and Emilia (2012) earthquakes, were found extensive damage to industrial structures, as pipelines, tanks, silos and buildings (Di Capua *et al.*, 2009; Grimaz and Maiolo, 2010; Lai *et al.*, 2012).

Based on the analysis of available reconnaissance reports (about 300 documents), a collection of damage cases was carried out, focusing the attention on a specific class of components of industrial plants (Table 1). From the observation of the post-earthquake damages to these industrial components, some brief remarks could be derived:

- underground structures suffered minor damages compared to the corresponding above-ground and semi-buried ones;
- seismic behavior improves with the increasing level of lateral confinement;
- many damage cases are referred to structures without anti-seismic devices or worn systems.

The seismic design methods for these types of structures and in particular for the pipelines, according to the current European Codes (EN 1998-4, 2006), are simplified and incomplete. Some indications were given about the pipelines for gas and oil transportation, which are mandatory designed as continuous pipelines (no weakness points at the joints), because they treat flammable and pollutant materials. Other notes are relative to the soil/structure interaction which is not negligible especially for buried pipelines; the hydraulic dynamic effects, instead, are generally considered negligible, except the case of wastewater system. Other design indications could be obtained from similar structures, using simplified hypotheses that need to be validated.

In the following, the main aspects related to the seismic performance of pipelines are discussed in order to clarify the methodology and point-out available knowledge and further research needs.

3. Performance-based analysis of the seismic behavior of the pipelines

The vulnerability analyses of the pipelines started from a systematic and thoughtful collection of the damage data based on the post-earthquake reports results. All the experimental data were classified and grouped to obtain four categories of parameters. The final goal of this data collection is the construction of new fragility curves for pipelines (Lanzano *et al.*, 2012, 2013a, 2013b), based on observational data, according to the approach described first elsewhere (Salzano *et al.*, 2003). The procedure is specifically oriented for industrial structures, which requires special tools (fragility curves and threshold values) in order to carry out Quantitative Risk Analysis (QRA) of the risk induced by natural catastrophic events (NaTech risks) (Campedel *et al.*, 2008).

The available fragility curves are generally not appropriate for this type of analyses, especially in the estimation of the damage levels and of the consequence of a possible loss of containment fluid. These specific aspects, relative to database classification and interpretation, are discussed in the next sections.

3.1. Seismological and geophysical parameters

Each collected damage data point was associated to a set of synthetic seismic parameter, in terms of peak ground acceleration (*PGA*), peak ground velocity (*PGV*) and modified Mercalli intensity (*MMI*). The data were generally obtained from the shaking maps of the relative earthquakes, knowing the exact location of the rupture or leak point. These maps are given, for instance, by the U.S. Geological Service (2012) and the synthetic data were checked using ground motion prediction equations (GMPEs), which are specific for the site under examination. Considering the uncertainties of shaking maps and GMPEs, the reference synthetic parameters are just an indication of the magnitude order of seismic action.

3.2. Relevant geotechnical parameters

The pipelines are frequently located underground and, in this case, the seismic behavior is strongly influenced by the surrounding soil. The collected damage data were divided into two groups, considering the seismic effects in the soil (O'Rourke and Liu, 1999): strong ground shaking (SGS) and ground failure (GF). The SGS is the common seismic effect due to the wave passage: the result is a deformation of the soil layer. The behavior of a continuous pipeline under SGS is usually approximated to that of an elastic beam subjected to the deformations field imposed by surrounding ground. Three types of deformations characterize 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.

The GF effects are failure phenomena induced by earthquake could be divided into 3 categories: a) fault displacement (GF1); b) liquefaction (GF2); c) landslide (GF3). The synthetic description of GF phenomena requires the correlation of the damage with a permanent deformation in the ground, which is the main cause of pipeline damage. Generally, the permanent movement is predominantly horizontal, except for the liquefaction cases, which are differently treated when it was considered lateral spread (GF2a, horizontal) or seismic settlement (GF2b, vertical). These effects are site dependent, because they depend on specific soil conditions (saturated fine loose sand for liquefaction, an active fault or a potentially unstable slope), which could induce the soil failure for a given earthquake loading. Obviously a study of soil failure susceptibility should be carried out before the study of soil/structure interaction.

3.3. Relevant structural parameters

From a structural point of view, the damage data on the pipelines breaks and leaks were classified according to constructive, geometric and operating parameters:

a) transported fluid (natural gas, oil, water and wastewater);
b) type (transmission/distribution, on ground/underground);
c) material (steel, plastic, cast iron and concrete);
d) joint type (welded, mechanical, special, etc.);
e) diameter/thickness of the pipelines (small D < 150 mm, medium D = 150 ÷ 400 mm and large D > 400 mm);
f) damage pattern (tension or compression, local or beam buckling, joint loosening, joint crush or circumferential cracks, loss of support, etc.).

In order to understand the seismic behavior of pipelines, these structures were divided into two categories in terms of damage patterns: continuous pipelines (CP) and segmented pipelines (SP). The main features, in terms of materials, joints and damage patterns, are showed in Table 2 and in Fig. 1. A similar approach has been already adopted in the context of HAZUS (FEMA, 1999), where the pipelines are divided into brittle (SP) and ductile (CP), on the basis of the seismic performance in terms of pre-failure deformations. Differently from simple HAZUS indications, the distinction was made in more accurate way.

The CP are generally made of steel and plastic materials and are used for transportation of natural gas and oil; the joints are frequently welded, but, more generally, they are designed in order to completely recover the resistance of the pipe body; the damage patterns are generally originated by tension/compression and buckling deformations along the pipe body.

The SP are used for water and wastewater transportation and are made by concrete materials or fragile cast iron; the joints are design and constructed in order to accommodate differential movement between two pipeline trunks; for this reason, generally, the pipeline weakness point is the joint itself and the damage is frequently located there; the tension/compression deformations

Table 2 - Some features of the industrial components investigated.

Pipelines	Materials	Joints	Damage pattern
Continuous (CP)	Steel; Polyethylene; Polyvinylchloride; Glass Fiber Reinforced Polymer	Butt welded; Welded Slip; Chemical weld; Mechanical Joints; Special Joints	Tension cracks (Fig. 1a); Local Buckling (Fig. 1b); Beam buckling (Fig. 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 (Fig. 1d); Crushing of Bell end and Spigot Joints (Fig. 1e); Circumferential Flexural Failure/pipe body cracks (Fig. 1f)

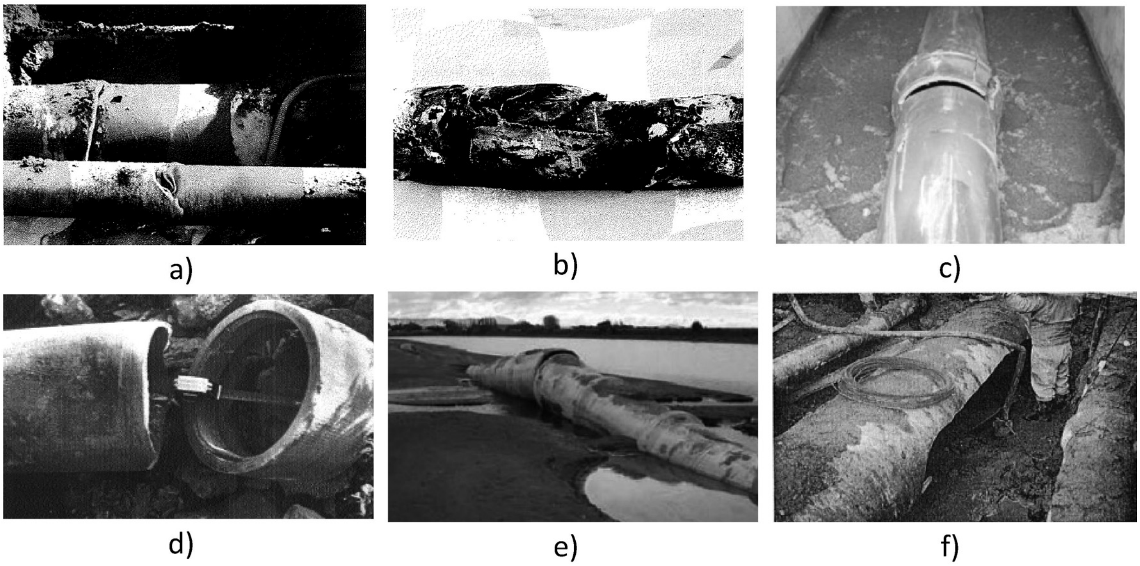


Fig. 1 - Damage patterns for pipelines: a) tension/compression cracks; b) local buckling; c) beam buckling; d) axial pull-out; e) crushing of bell end and spigot joints; f) cracks along the pipe body [Lau *et al*., 1995 (a,b); Tanaka *et al*., 2011 (c); Ayala and O'Rourke, 1989 (d); Allen *et al*., 2010 (e); Kameda, 2000 (f)].

cause the pull-out or the crushing of the joints, instead the buckling strains are related to circumferential cracks in the joint location and along the pipe body.

3.4. Measure of the seismic performances in view of Na-Tech applications

Each damage data point was recognized as performance indicator of the pipe, based on the damaging level occurred to the structure. The approach is different from the estimation usually performed, which is expressed in terms of repair rate (number of repairs for pipeline unit length), and does not account the damaging level (American Lifeline Alliance, 2001).

For the classification, the damaging levels were calibrated considering the entity of damage in terms of service stop and loss of containment (Table 3). These criteria, as for the structural aspects, were derived and extended from HAZUS, which simply classified breaks and leaks. In

Table 3 - Damage levels for the 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.

this research, a better definition for these classes was given, adding an initial DS0 “no damage” class, relative to all the damaging effects that does not affect the system functionality or not cause the material leakage (for example the support loss for aboveground pipelines).

The DS1 is similar to HAZUS “leak” class. Therefore, in this class, the damages with limited amount of fluid loss or time distributed leakage were associated; some significant damage patterns were associated to this damage class, including compression and buckling deformation for CP and joint crush and circumferential cracks for segmented pipelines.

The DS2 class is relative to the instantaneous loss of a large amount of fluid containment (“breaks” after the HAZUS classification) and is associated to tension breaks and joint pull-out, for CP and SP respectively.

According to such a classification, a damage state is associated to each data point, together with seismological, geotechnical and structural synthetic aspects. In the next section the database was examined.

4. Post-earthquake damage data

The collected data were referred to 22 different earthquakes from 1906 to 2012. The damage cases were about 400. The selected and analyzed earthquakes are listed in Table 4 with the damages number, year, moment magnitude and the main reference for the data collection. All the data were divided into 5 classes, which are considered significant for fragility curves construction: Above-ground pipelines (AP); buried CP under SGS (CP-SGS); buried CP under GF (CP-GF); buried SP under SGS (SP-SGS); buried SP under GF (SP-GF). In Fig. 2, the relative amount of each of these classes was showed.

The largest class (33%) is relative to CP under transient deformations (caused by SGS), accounting a total of 160 cases. A significant data amount is given to both the GF classes (20% for CP and 23% for SP); a relatively small amount of damage cases was found for SP under SGS (7%) and for AP (13%), which need a database enlargement. More than 40% of pipelines damage cases are due to the ground failure phenomena, which corresponds to about 160 cases from the 1906 San Francisco earthquake to 2010 Darfield earthquake in New Zealand. All the cases were again divided both for specific ground failure phenomenon and damage class in the Fig. 3. Most of the available data are relative to laterals spread and almost 50% of the observed pipelines under this phenomenon suffered heavy damage. Observed cases of damage due to active faults and seismic settlement are in a lower number, considering that all the cases of

Table 4 - List of analyzed earthquakes.

N°	Earthquake	Year	Damage Cases	Moment magnitude *Mw*	Main Reference
1	San Francisco	1906	45	7.8	Eidinger 2003
2	Long Beach	1933	1	6.3	O'Rourke and Palmer 1996
3	Kern County	1952	17	7.3	O'Rourke and Palmer 1996
4	Anchorage	1964	2	9.2	Eckel 1967
5	San Fernando	1971	117	6.7	O'Rourke and Palmer 1996
6	Imperial Valley	1979	3	6.5	O'Rourke and Palmer 1996
7	Michoacán	1985	12	8	Ayala and O'Rourke 1989
8	Whittier Narrows	1897	29	5.9*	Schiff 1988
9	Loma Prieta	1989	18	6.9	O'Rourke 1992
10	Valle della Estrella	1991	2	7.6	Ballantyne *et al.* 1991
11	Erzincan	1992	19	6.6	Tilford and Ballantyne 1993
12	Hokkaido	1994	19	8.3	Koseki *et al.* 2000
13	Northridge	1994	58	6.7	O'Rourke and Palmer 1996
14	Kocaeli	1999	4	7.4	O'Rourke *et al.* 2000
15	Chi-Chi	1999	2	7.7	Hwang *et al.* 2004
16	Quinghai-Xinjiang	2001	1	7.8	Guo *et al.* 2004
17	Denali	2002	11	7.9	Sorensen and Meyer 2003
18	Achaia-Ilia	2008	1	6.5	Margaris *et al.* 2008
19	L'Aquila	2009	3	6.3	Esposito *et al.* 2011
20	Maule (Chile)	2010	8	8.8	Acuna 2010
21	El Mayor	2010	1	7.2	EERI 2010
22	Darfield	2010	19	7.1	Allen *et al.* 2010
	Total		392		

*Local magnitude ML

vertical settlement are relative to the case of Marina district during the Loma Prieta earthquake (O'Rourke, 1992). Some cases are related to failure induced by landslide, but these are very strong and destructive events (for example two cases are relative to 1964 Alaska earthquake), that caused extensive damage to the interacting pipelines (Eckel, 1967).

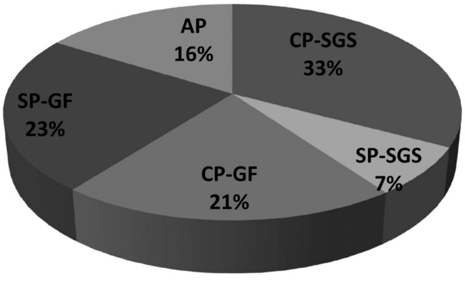
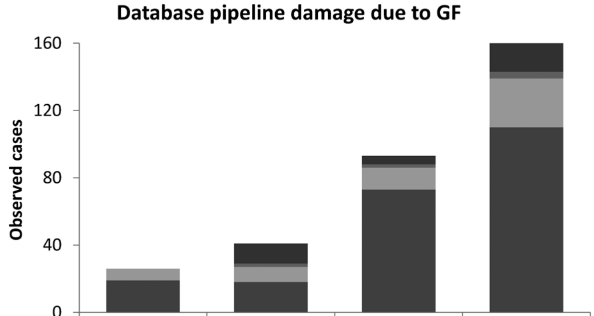


Fig. 2 - Chart for the relative amount of damages for each class of data.



	DS0	DS1	DS2	All
■ Seismic settlement	0	12	5	17
■ Landslide	0	2	2	4
■ Active fault	7	9	13	29
■ Lateral spread	19	18	73	110

Fig. 3 - Distribution of the observed case accounting GF type and DS.

All the data were divided on the basis of geotechnical aspects and were plotted (Fig. 4) as histogram graphs vs. the reference synthetic seismic parameter. For the strong ground shaking data, the reference parameter is the *PGV*, which is the most used indicator for SGS fragility construction (Pineda-Porras and Najafi, 2010) and it is related to soil deformation; therefore the *PGV* is used to estimate the maximum longitudinal deformation along the pipelines according to the Newmark (1967) expressions. The reference parameter for ground failure is the permanent ground displacement (PGD) or δ, which is a performance-based parameters, useful to compare the response of soil to different failure phenomena, which have different seismic and geotechnical input parameters.

The comparison of Fig. 4a shows that most of the DS1 cases are relative to a velocity range between 10 and 60 cm/s; instead, in order to obtain DS2 cases, a higher level of *PGV* is required (most of the data are in a range between 60 and 100 cm/s).

For the GF cases (Fig. 4b) the number of DS0 states tend to decrease with the increment of δ; most of the cases occurred for the lowest values of permanent displacement ($0 \text{ m} < \delta < 0.4 \text{ m}$), especially for the cases of lateral spread (in gently slope conditions) and seismic settlement; an increment of damage cases in the data distribution for $\delta > 1.6$ m was clearly observed, mainly due to occurrence of active fault cases.

Based on some of the mentioned classification criteria, which are, in some cases, mutually dependent, data were reported in the form of histograms in Fig. 5. Some brief comments can be proposed:

a) most of the damage were found for small and medium diameter pipelines, generally used for the distribution system; less damage for transmission system;

b) most of the pipelines were made by steel, which was used both for natural gas and water pipelines; despite of this consideration, many DS2 cases for the cast iron pipelines were found;

c) most of the used joints are welded; this aspect is related to the large amount of steel pipelines (Fig. 5b), because the joints for this material are commonly welded, with variable execution technologies;

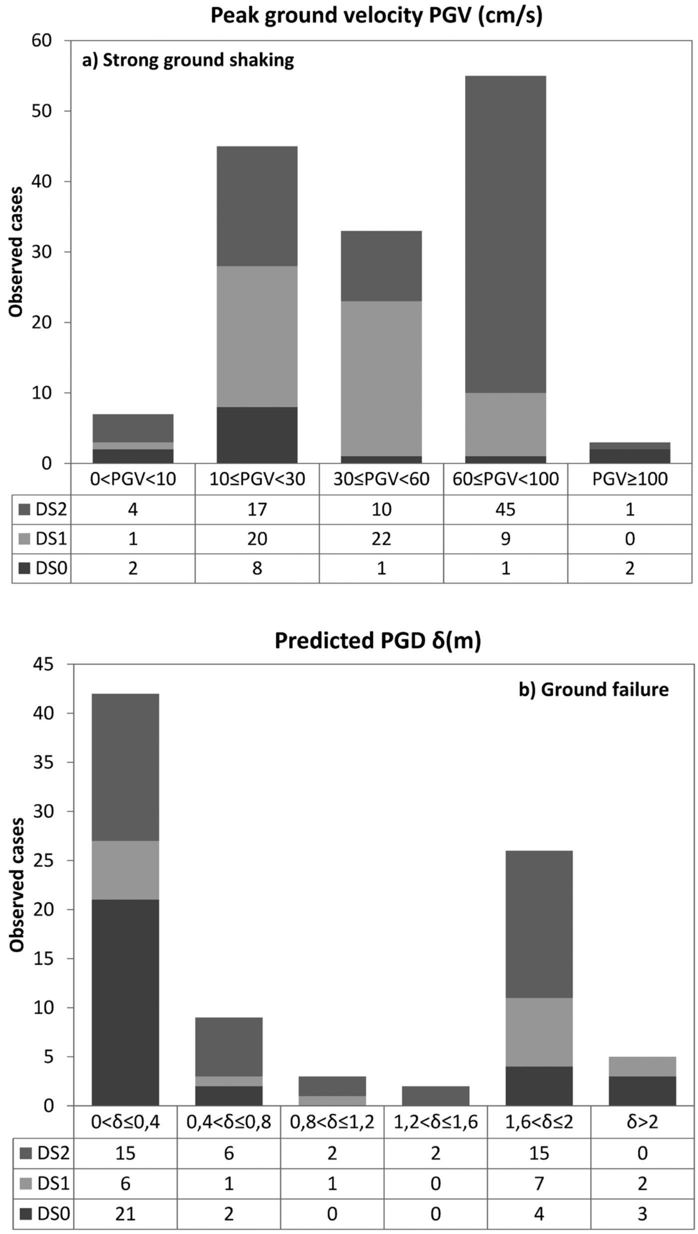
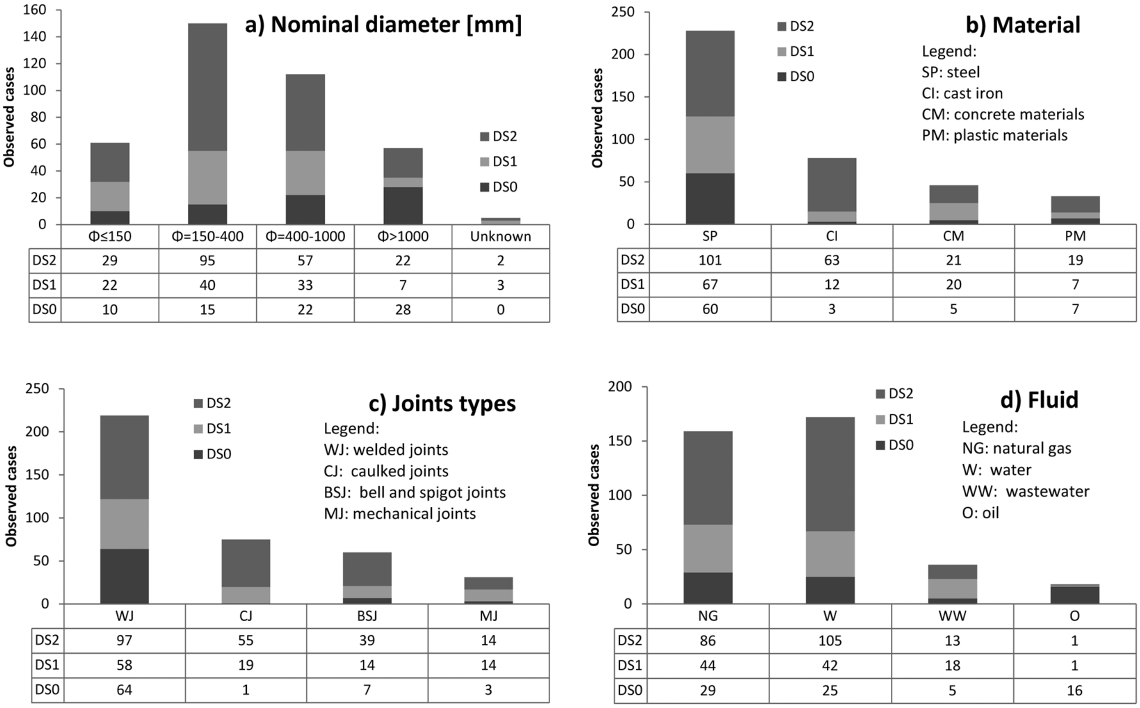


Fig. 4 - DS distribution depending on a) PGV for SGS cases and b) PGD for GF cases.

d) many damage cases are relative to natural gas and water pipelines; a less amount for wastewater system and oil (which is general similar to natural gas pipelines from a structural point of view).

The analyzed amount of data is going to increase and a more detailed description of each single damage case is under development in association with the outcomes of theoretical-experimental comparisons.

A final outcome of the study is certainly the assessment of pipelines systems not only at regional and urban scale, but also in the context of large industrial areas. Failures and



	Φ≤150	Φ=150-400	Φ=400-1000	Φ>1000	Unknown
DS2	29	95	57	22	2
DS1	22	40	33	7	3
DS0	10	15	22	28	0

	SP	CI	CM	PM
DS2	101	63	21	19
DS1	67	12	20	7
DS0	60	3	5	7

	WJ	CJ	BSJ	MJ
DS2	97	55	39	14
DS1	58	19	14	14
DS0	64	1	7	3

	NG	W	WW	O
DS2	86	105	13	1
DS1	44	42	18	1
DS0	29	25	5	16

Fig. 5 - DS distribution depending on a) nominal diameter, b) material c) joint types and d) transported fluid.

malfunctions due to even medium to low intensity earthquakes can affect the results of QRA analyses and need to be well established in order to develop reliable and sustainable guidelines for risk and consequence mitigation.

5. Conclusions

The research, reported in the present paper, has been focused on the seismic vulnerability of special categories of industrial components, as pipelines, underground tanks and buried basins, whose response is affected by a multiple interaction between soil, structure and fluid. In particular, some aspects related to the pipelines were discussed according to a multidisciplinary approach between geotechnical, structural and geophysical knowledge. This paper presents some aspects of the collection of data referring to damage suffered by pipelines during the past earthquakes. Such information is an essential tool in order to assess on experimental basis the seismic vulnerability of these components. It is worth noting the relative large amount of this data could be used to build up fragility curves, but also provide a stable background for the development of numerical validations and results extension. These are the reasons why the database is continuously increased with new data coming from past and recent earthquakes in order to refine fragility formulation and support the relevant parameter selection in view of advanced theoretical analyses and laboratory tests on selected components.

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