Multidisciplinary approach for the seismic vulnerability evaluation of lifelines and structural components of industrial plants

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SUMMARY:
Industrial plants and lifelines play a crucial and essential role in the human life and in the economic development of a country: for this reason, their structural safety under extreme events, like strong earthquakes, must be ensured, especially when a large amount of toxic and flammable material were stocked and transported in these structures. Therefore, a multidisciplinary study was carried out to evaluate the seismic vulnerability of a set of industrial structure and lifeline, like pipelines, underground tanks and basins. In this paper, a specific approach was developed for the study of seismic vulnerability of pipelines. To this end, a large amount of damage data to pipelines was collected from post-earthquake reports, in order to obtain a reference database. All the data were classified accounting different topics, including material, transported fluid, geotechnical aspects, diameter, joints, seismic parameters. These data were analyzed and checked using simplified expressions and were used to build the fragility formulations for different classes of pipelines.

Keywords: Pipelines; Seismic performance; Permanent displacement, Industrial components.

1. INTRODUCTION

Industrial plants are strategic structures for economic and social development of a country. A primary requirement for industrial plants and their fundamental components is to ensure their structural safety, especially when large amount of toxic and flammable substances are stored or manipulated. A key aspect in the broad topic of the safety of industrial plants is the seismic vulnerability.

Among the very large number of structural and non-structural components of the industrial plants, pipelines, underground tanks and buried and semi-buried basins are largely used and need special attention because of the very complex behaviour under seismic actions, requiring a multi-disciplinary approach to be exhaustively analysed. .

As a matter of fact, for this class of structures, in addition to structural and seismological knowledge, expertise in geotechnical and hydraulic engineering are needed, because in all the class cases the structures are surrounded of ground and contain a fluid. Therefore, in a full approach, a multiple soil/structure/fluid interaction should be considered, accounting for the geometrical, physical and mechanical properties of these three components.

Both in past and recent earthquakes occurred during the last decades these structure still suffered heavy damage, despite the evolution in the anti-seismic techniques and the progress in the seismic design. Significant cases of damage could be observed both in the historic earthquakes of San Francisco (1906), Northridge (1995) and Kobe (1995), and in the recent earthquakes of L'Aquila (2009), Darfield (2010), Chile (2010) and Tohoku (2011). On the basis of the large amount of data concerning the seismic behaviour of these structures during the above listed earthquake, a complete collection of cases was carried out, in order to build a database with the scope of study the damage mechanism and to back-analysing the described event according the available knowledge.

Frequently, this approach has been carried out in order to obtain a novel formulation of the fragility curves able to support quantitative industrial risk analyses including external natural hazards, like earthquakes (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 specific fragility analysis a performance indicator is expressed in function of a dose parameter, which is, in these seismic analyses, a synthetic parameter of the earthquake motion. In this paper some indications on the data collection were given, focusing the attention on the damage cases of pipelines. The methods to analyze databases of damages of pipelines are discussed here, showing some synthetic results.

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;
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. In this paper the main important topics of geotechnical and structural engineering are reported, focusing on the gas pipelines (continuous) and neglecting the hydraulic effects, as suggested by the Eurocode.

3. GEOTECHNICAL ASPECTS FOR PIPELINE BREAKS

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 (GF1), liquefaction (GF2) and landslides induced by the shaking (GF3). 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 GF2 phenomenon).

In the next subsections, simplified methods to obtain the soil deformation in SGS conditions and the permanent ground displacement in GF conditions are discussed. Moreover simple methods to study the soil/pipeline interaction are considered, in order to evaluate the earthquake-induced strain in the pipeline and compare this one with the material strength in each examined case.

3.1. Strong ground shaking

The seismic design of underground structures under SGS is based on the prediction of the ground displacement field. 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:

$$\varepsilon = \frac{PGV}{V_R} \tag{3.1}$$

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.

3.2. Ground failure

In order to study and analyzed the seismic behaviour of pipelines underground failure condition, a reasonable estimation of the permanent ground displacement is always needed. The main important types of PGD are (O'Rourke and Liu 1999):

a) Horizontal and/or vertical displacement induced by surface active faults;
b) Horizontal and/or vertical displacement due to earthquake-induced landslides;
c) Horizontal displacement due to liquefaction phenomena on inclined surfaces (lateral spreading);
d) Vertical displacement due to the densification of loose sands under groundwater level because of liquefaction (seismic settlement);

Except for the case of seismic settlement, the permanent displacement is in most of the cases predominantly horizontal. The effects of PGD are generally limited to finite regions in the pipelines system, but the damage potential could be high when the expected permanent deformations are large and generally higher compared to the strong ground shaking cases.

Lanzano et al. (2012a) described some significant empirical or analytical relations for the permanent ground displacement evaluations. Some features of the expressions used in the back-analysis of the database were showed in Table 3.1: in particular the significant parameters for δ estimation and the principal references of the empirical/analytical formulation.

Table 3.1. Input parameters for permanent ground displacement δ

Ground Failure	N°	Type	Reference
Active fault	1	M_w	Wells and Coppersmith (1994)
Lateral spread	4	M_w, R, S (or Y), H_1	Bardet et al. (1999)
Landslide	3	M_w, R, a_y	Jibson and Keefer (1993)
Seismic settlement	3	PGA, H_1, N_{av}	Takada and Tanabe (1988)

In the table, M_w is the moment magnitude of the earthquake, R is the epicentral distance, PGA is the peak ground acceleration; S and Y are two topographical parameter showed in Figure 1 for gently slope and free-face conditions; H_1 is the thickness of liquefied (or liquefiable) soil; N_{av} is the average value of number of blows of the SPT test in the thickness H_1; a_y is the critical acceleration according to

the Newmark (1965) scheme of rigid block for the potential landslide.
The expression for the active fault included the results of previous studies adding other observed data. The maximum fault displacement PGD, according to Wells and Coppersmith (1994) approach, is evaluated as two times the value of δ.

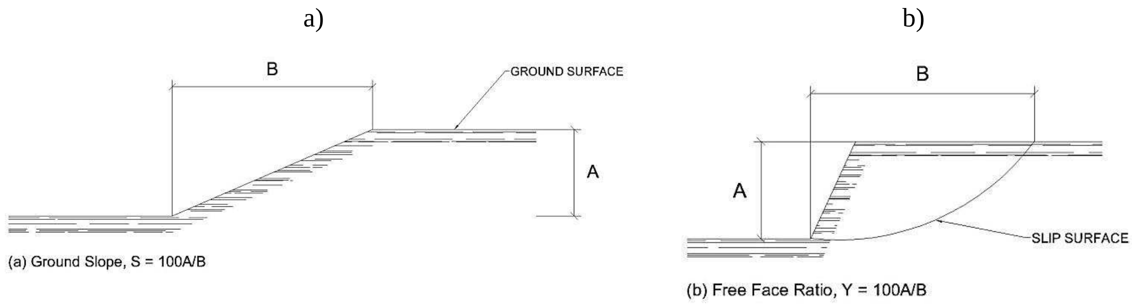

Figure 1. Scheme for gently slope (a) and free-face conditions (b) for lateral spread PGD estimation.

Various empirical formulations were proposed to predict the permanent ground displacement in lateral spread conditions (i.e., Bartlett and Youd, 1992 and Bardet et al., 1999), based on geometrical, seismological and geotechnical parameters. Bardet et al. (1999) obtained simplified correlations based on 4 parameters, which are easier to use in the practice.
Takada and Tanabe (1988) gave an empirical estimation of the liquefaction-induced settlement for saturated loose sands in two different site condition (plain sites and embankments). This approach gave a simple and easy estimation of the seismic settlement, but in order to obtain a reliable result, a description of the site condition through borehole and in-situ tests are necessary.
Many analytical estimations of permanent ground displacement δ due to earthquake-induced landslides are available in literature. Most of them are referred to rotational and planar slides and are based on the method of rigid block of Newmark (1965): the predictive expressions were given from the different authors on the basis of different synthetic seismic parameters. Jibson and Keefer (1993) gave an analytical estimation of the permanent ground displacement expected from an earthquake-induced landslide, which is expressed in function of Arias Intensity I_a and critical acceleration a_y. In our analyses an attenuation law was used in order to estimate the Arias Intensity on the basis of moment magnitude M_w and epicentral distance R (Wilson and Keefer 1983).
The horizontal movement induced by active fault is generally confined in very confined areas; for this reason, the estimation of δ and the fault type are sufficient to study the soil/pipeline interaction. A simple model for estimation of continuous pipeline strain induced by strike slip fault horizontal movement was developed by Newmark & Hall (1975).
On the contrary of fault, in order to study the pipelines response in lateral spread and landslide conditions, more geometrical parameters of the horizontal displacement are needed for soil/pipeline interaction study (Figure 2):

a) the total amount of permanent displacement δ_h;
b) the transversal width of the PGD area W;
c) the longitudinal length of PGD area L;
d) the distribution model of the displacement along the PGD area (PGD patterns).

Considering the requested parameters, a complete description of these phenomena is a very complex problem, because it is not only a simple estimation of the horizontal permanent displacement, but also the areal extension and the spatial evolution of the phenomenon are needed. Nevertheless, some empirical, analytical and numerical studies were carried out to describe the phenomena.
O'Rourke and Norberg (1992a), following the approach of Suzuki and Masuda (1991) on an increased database of empirical observations, showed that a linear correlation exists between the amount of permanent ground displacement d and the length L and width W of a lateral spread area in gently slope conditions. The linear coefficient k to be multiplied to δ is ~133 for the length L and ~348 for the width W. Concerning the PGD pattern, most of the observed distributions of δ are showed by O'Rourke and Norberg (1992b): in those cases the calculated PDG is the maximum value of the

distribution. In the following consideration of soil/pipeline interaction, the considered PGD pattern is the one that maximized the pipeline strain induced by ground failure phenomenon.

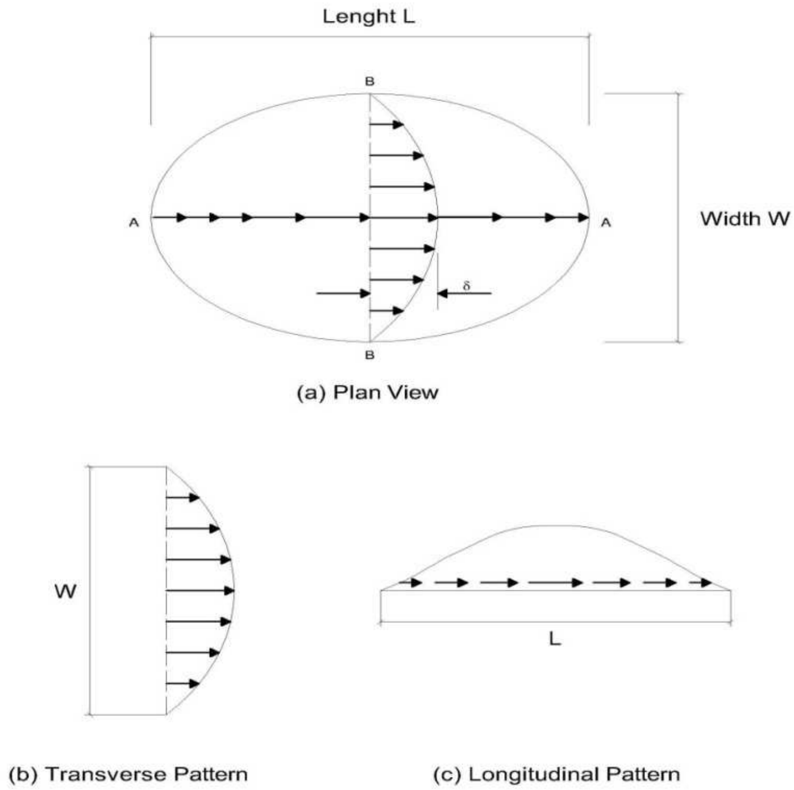

Figure 2. Significant geometric parameters for the seismic pipeline response in GF conditions.

Once the amount and the spatial entity of the lateral spread and landslide phenomenon are full described, the soil/pipeline interaction should be accounted other significant aspects:

a) the relative position between the pipeline trace and the direction of the horizontal movement: in limit conditions, the horizontal motion could be considered longitudinal or transversal to the pipeline trace;
b) considering the soil properties modifications for liquefied soil, in terms of strength reduction, different behaviour should be expected for pipeline surrounded by liquefied or competent soil.

In the next section, the maximum strain induced by PGD was evaluated considering a block pattern (constant δ along L) for longitudinal displacement and a β distribution of δ along W for transversal displacement, according to O'Rourke and Liu (1999) indications. The surrounding soil was considered as competent in all the case, which is the most common situation for pipeline, because frequently the top of liquefied layer is under the pipeline bottom (O'Rourke and Liu 1999). Based on this simplified assumption the maximum earthquake-induced strain was evaluated for continuous pipeline using an elastic model for the structure.

4. STRUCTURAL ASPECTS FOR PIPELINE BREAKS

As for the structural aspects, damage patterns occurred in the pipelines are various and largely dependent by a number of features of the structures, such as the material base properties and the joint detailing. Table 4.1 summarises all the most relevant aspects from the structural perspective and shows all the possible combinations of material and joints.

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.

Table 4.1. Structural aspects in the seismic behaviour of pipelines

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 (Figure 3a); Local Buckling (Figure 3b); Beam buckling (Figure 3c)
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 3d); Crushing of Bell end and Spigot Joints (Figure 3e); Circumferential Flexural Failure and Joint Rotation (Figure 3f).

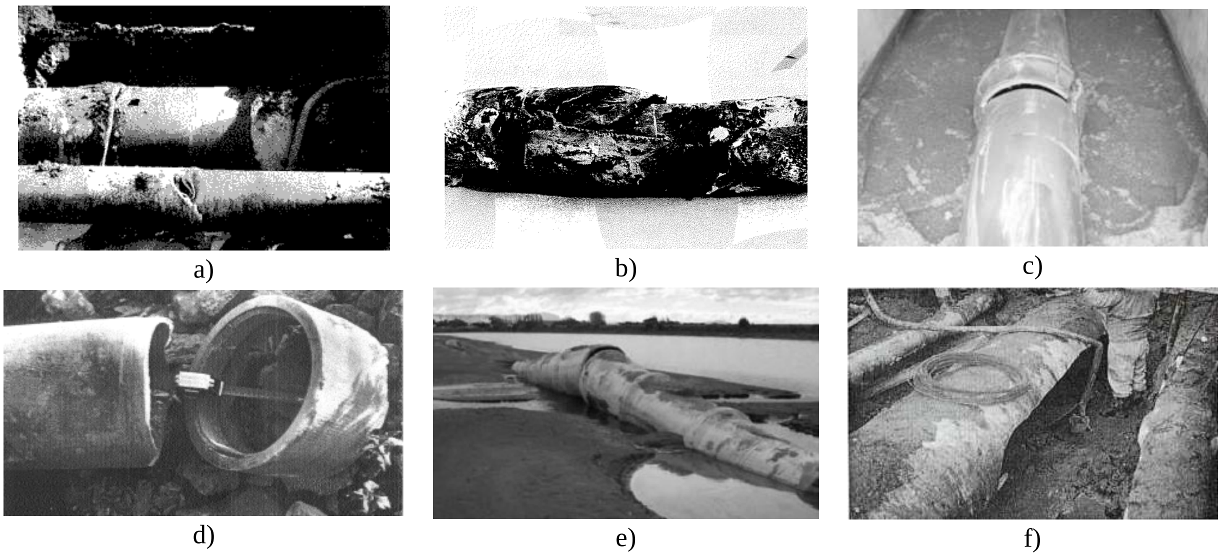

Figure 3. Damage patterns for pipelines: a) tension/compression cracks; b) local buckling; c) beam buckling; d) axial pull-out; e) crushing of bell end and spigot joints; f) cracks along the pipe body (Lau et al., 1995 (a,b); Tanaka et al., 2011 (c); Ayala and O'Rourke, 1989 (d); GEER, 2010 (e); Kameda, 2000 (f)).

The maximum strains evaluated from the simplified methods (for example Equation 3.1), based on the specific geotechnical features, were compared with the limit deformation, accounting the different damage patterns, materials, joint type, according to the table, for each investigated case (Hall and Newmark, 1977). The entire database was checked, examining the possibility that the damage were likely.

4.1. Performance based indicators for pipelines

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), PGV2/PGA and PGD1 (Peak Ground Displacement); GF: 7 fragility formulations with seismic intensity indicators PGD2 (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.
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). The damage indicators (Table 4.2) are properly recalibrated from the simplified classification of Hazus (FEMA, 1999), 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).

Table 4.2. 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. PRELIMINARY RESULTS

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). In Figure 4, the database was divided in 5 classes, accounting both structural (CP or SP; buried or aboveground pipelines AP) and geotechnical aspects (SGS and GF).

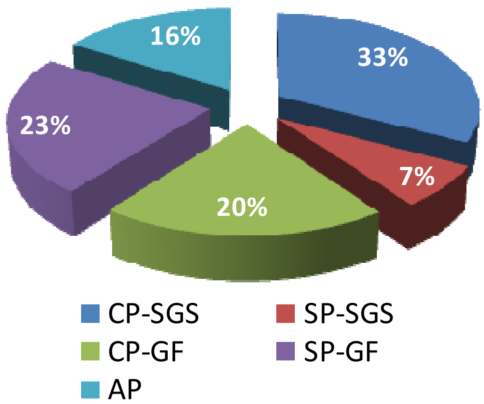

Figure 4. Chart for the relative amount of damages for each database classes.

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; the amount of damage cases relative to strong ground shaking is around 40%, but most of all are relative to continuous pipelines (33%) as gas pipelines. The remaining part (16%) is relative to aboveground pipelines, for which the damage is frequently connected to the loss of support during the seismic shaking.
All the GF cases were accurately analyzed and a reasonable estimation of the PGD was obtained considering the availability and quality of the collected cases. The previous empirical and/or analytical formulations were used to calculate the permanent displacement, obtaining the input parameters on the basis of field data, seism-tectonic studies, large and small scale mapping and, in the worst cases, on the engineering judgment. When a field measurement of PGD was available, a comparison between

predicted and measured displacement was carried out. A good agreement between measured and predicted permanent ground displacement is evident in the Figure 5, showing few “out of trend” cases, which need further studies.

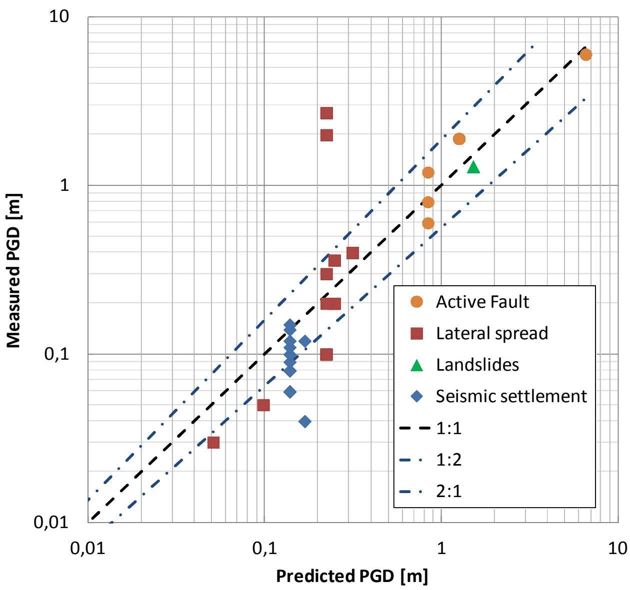

Figure 5. Comparison between predicted and measured permanent ground displacement.

The pipelines under strong ground shaking, similarly to GF cases, were back-analyzed and the checked data were used to build up a preliminary fragility formulation, in particular for the case of continuous pipelines (Lanzano et al. 2012b).

5.1. Preliminary Fragility curve and probit function for continuous pipelines under SGS

The seismic vulnerability of the continuous pipelines under strong ground shaking has been estimated by using the classical probit analysis (Finney 1971). The probit variable Y is expressed in the Equation (5.1), 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.

$$Y = k_1 + k_2 \ln V \tag{5.1}$$

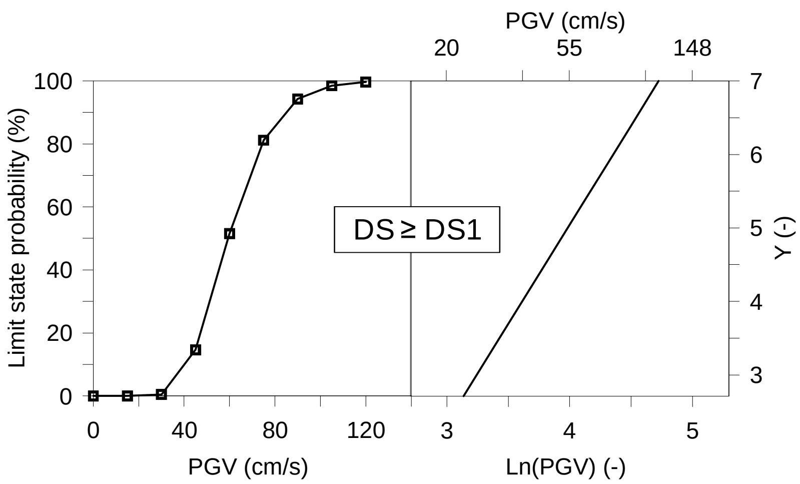

Figure 6. Preliminary fragility (left) and probit (right) function for continuous pipelines under SGS.

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 are shown in Figure 6, 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 5.1, 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.

Table 5.1. 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

6. CONCLUSIONS

The industrial plants need special attention when the seismic structural safety and interaction between natural hazards and process functionality and risk are of interest. This is much more relevant whenever structural damage or loss of a toxic or flammable handled material can cause a serious risk for human life, environment and economy.

In this paper the main relevant aspects of the seismic hazard of the pipelines are discussed, which are a widely used structural component of the industrial plant for the transportation of fluids. The study of seismic behaviour was carried out through a multi-disciplinary analysis of a collected database of damage occurred to pipelines during the recent documented earthquake. The available damage cases were analyzed according to geotechnical and structural relevant topics, in order to evaluate the soil/structure interaction and estimate the pipeline response under the seismic loadings. The final goal of the research is to build up specific fragility formulations for this class of industrial components, accounting the multidisciplinary nature of this research. A preliminary fragility and probit curve for continuous pipeline under strong ground shaking is given. A novel performance indicator has been proposed in order to fit requirements for standard industrial risk analyses. It overcomes the applicative issues related to the available fragility formulations for pipelines, which are based on a global repair rate and not on each single damage mechanism analysis.

AKCNOWLEDGEMENT

The authors wish to thank the ReLUIS Consortium, for the economical and scientific support on the project ReLUIS 2 (2010-2013), and the coordinators of the Line 2.2 “Special Structures” (Prof. Edoardo Cosenza) and Line MT.1 Geotechnical Engineering (Prof. Francesco Silvestri). Moreover the authors wish to thank the young students of the University of Molise Region, Ramona Tucci and Giuseppe di Nunzio, for the collaboration in the data collection and interpretation.

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