ExchangeRisk

EXperimental & Computational Hybrid Assessment of Natural Gas Pipelines Exposed to Seismic Risk

Critical damage modes and intensity measure efficiency of NG pipelines

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Potential damage modes

- **Earthquake-induced transient ground deformation can trigger various damage modes on continuous pipelines, including (O'Rourke and Liu, 1999):**
  - **shell-mode or local buckling**
  - **beam-mode buckling**
  - **tensile rupture**
  - **flexural bending failure**
  - **excessive ovaling deformation of the section**

Shell-mode or local buckling

- **Shell-mode or local buckling is associated with the loss of stability caused by compressive or bending loading on the pipeline and is likely to occur in deeply buried large diameter pipelines with high R/t ratio**

- **O' Rourke & Liu (1999) reported a local buckling failure of a 406 mm diameter steel gas pipeline during the 1972 San Fernando earthquake**

- **Local buckling due to seismically-induced transient ground deformations was also reported on a large diameter steel pipeline during the 1985 Michoacán earthquake in Mexico City (O' Rourke 2009)**

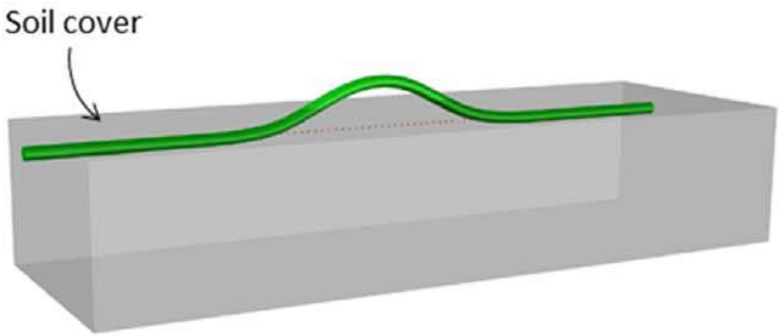
Beam buckling

- Beam or upheaval buckling, which likely to occur in cases of shallow small-diameter pipelines with low R/t ratio, resembles the Euler buckling mode of column subjected to compressive loading

- This damage mode rarely leads to breakage but it may affect the serviceability of the pipeline by reducing the flow of content

- O'Rourke & Liu (1999) reported cases of beam buckling failures of small diameter oil and gas pipelines due to fault movements during the 1979 Imperial Valley earthquake

- Mitsuya et al. (2013) reported several cases of beam buckling on small diameter NG pipelines during the 2007 Niigataken Chuetsu-oki earthquake



Tensile rupture

- Corrosion free steel pipes with arc-welded butt joints are capable of mobilizing large strains with significant tensile yielding before rupture due to their high ductility

- On the contrary, tensile rapture might be an issue for old pipes with gas-welded joints, which can not tolerate large tensile strains before rapture

- O'Rourke & Liu (1999) reported that this failure mechanism was more evident for pipelines subjected to permanent deformations due to seismically-induced ground failures

Flexural bending failure

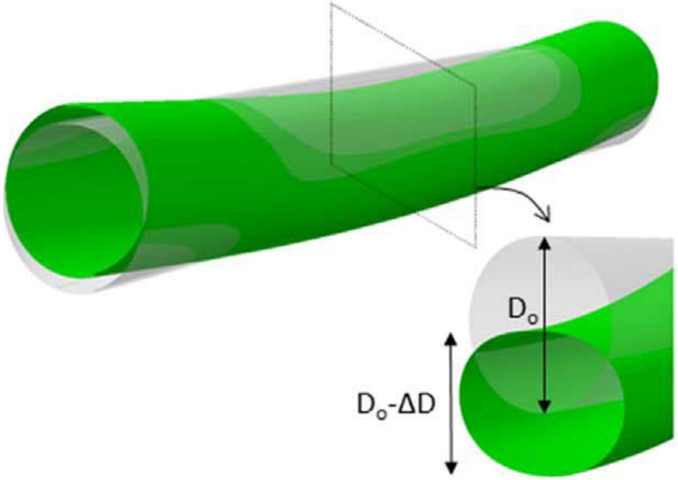
- **Flexural failure of steel pipelines, due to excessive bending loading, is rarely expected in gas pipelines, due to the high ductile materials used, i.e. steel or polyethylene**

- **Instead, excessive bending may lead to beam buckling or ovalization of the pipeline, depending on the radius to wall thickness ratio**

Sectional ovalization – Brazier effect

- **Large radial deformations of the section caused by significant bending forces, may lead to a flattening of the circular cross section**

- **Although this failure mode is not affecting the structural integrity of the pipeline, it may be considered as a serviceability threat for the pipeline, since it reduces the flowing capacity**



Seismic risk assessment for embedded pipelines

- **General lack of rigorous methods and detailed standards for the seismic risk assessment of NG pipelines**

- **References and fragility curves, referring to other typologies of buried pipelines, are commonly used for the assessment of NG pipelines**

- **Probabilistic empirical fragility relations have been proposed over the last 40 years for buried pipelines, based on post-earthquake observations of their response**

- **A few recent studies (Lee et al., 2016, Jahangiri and Shakib, 2017) have employed numerical approaches to construct probabilistic analytical fragility curves, in the sense of the following definition:**

$$Fragility = P\left[D \geq C \middle| IM \right]$$

Efficiency of available fragility relations for pipelines

- The majority of empirical fragility relations implement the pipeline repair rate, as the EDP, i.e. the number of pipe repair per unit length, without disaggregating between leaks or more severe breaks and more importantly, without providing detailed information about the failure mode

- The accuracy of repair reports that constitute the basis for the development of empirical fragility functions may be questionable, since these are commonly drafted after a short period from the main event and under the pressure for rapid restorations

- Applicability? Most of available relations were developed based on post-earthquake observations of the response of NG pipelines in USA and Japan

- The limited analytical fragility functions do not cover all NG pipeline typologies and do not distinguish between various damage modes and associated consequences

Seismic intensity measures for embedded pipelines

- **Various seismic intensity measures have been adopted for the development of empirical and analytical fragility relations:**
  - **Modified Mercalli Intensity, MMI**
  - **Peak Ground Acceleration, PGA**
  - **Peak Ground Velocity, PGV**
  - **Peak Ground Strain, ε_g**
  - **Arias Intensity, I_a**
  - **PGV^2/PGA**
  - **Spectral Acceleration (SA) or Spectral Intensity (SI)**

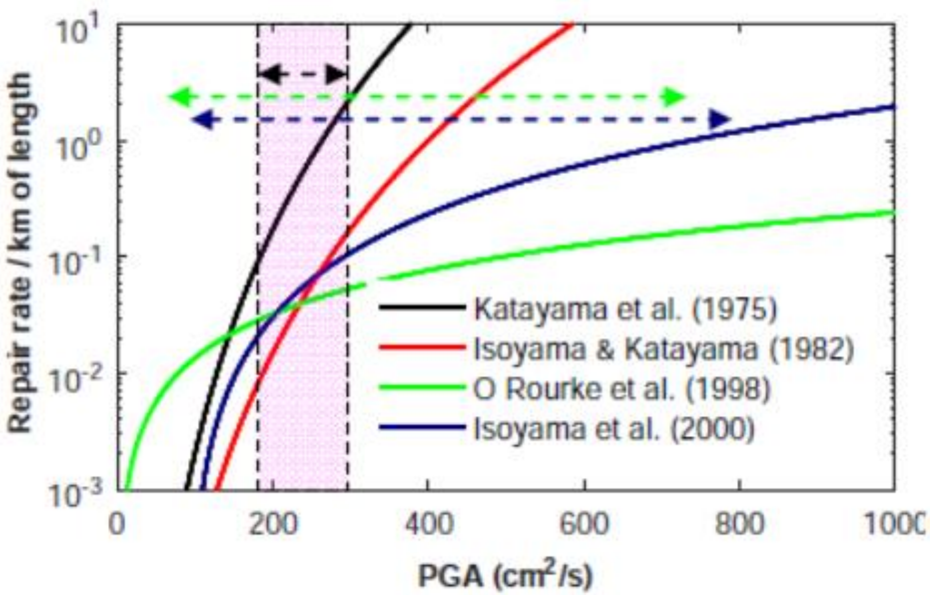
Modified Mercalli Intensity (MMI)

- **MMI was used as IM in early studies due to the absence of extensive instrumental records of the ground motion**

- **The subjective nature of its definition, introduces a high level on uncertainty, making MMI an inadequate IM for a quantitative seismic risk assessment of pipelines**

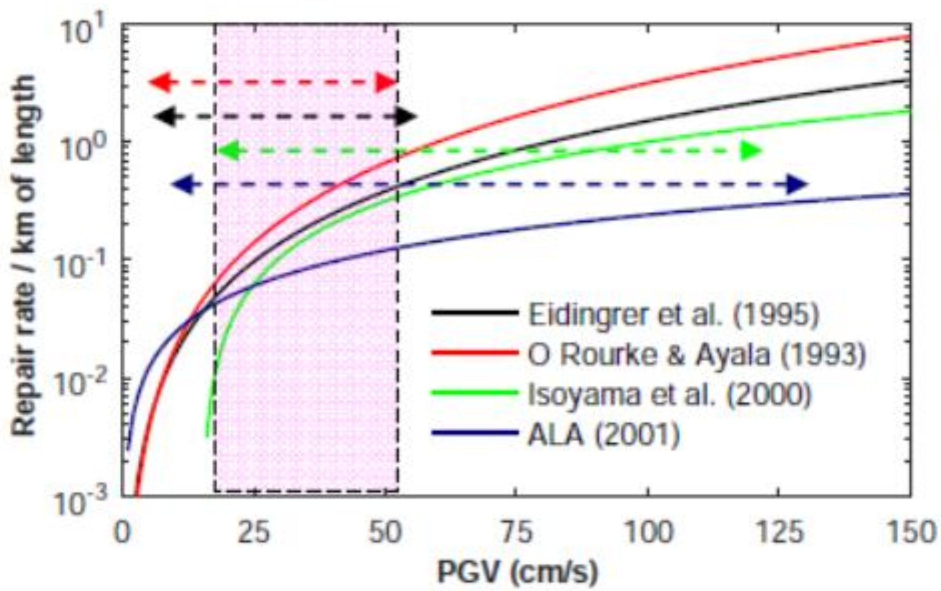
Peak Ground Acceleration (PGA)

- Measure of the amplitude of the seismic ground motion
- Can easily by obtained through: (1) recorded acceleration time histories , (2) Ground Motion Prediction Equations (GMPE), (3) shake maps, (4) stochastic simulation of the ground motion (mainly during pre-seismic evaluations of existing critical networks)
- Generally, PGA correlates directly with inertial forces, which are of minor importance for buried structures
- Many early studies developed empirical fragility relations for buried pipelines using PGA as IM – significant differences between the relations



Peak Ground Velocity (PGV)

- **PGV has been extensively used as IM in empirical fragility relations for pipelines, since it can be related to the longitudinal ground strain, which is responsible for induced damages on pipelines**
- **PGV can be obtained through: (1) integration of recorded acceleration time histories, (2) GMPE that correlate directly PGV with multiple seismological parameters, (3) shake maps, (4) PGV/PGA relations (e.g. ALA, 2001)**
- **Noticeable deviations between various fragility curves; however, slightly lower compared to PGA-based fragility curves**



Peak Ground Strain (PGS)

- **Peak ground strain is directly related to the seismic performance and fragility of embedded pipelines**

- **PGS may be computed from displacement time histories of the ground motion:**

$$PGS = \max\left|\varepsilon(t)\right| = \max\left|\partial D(t)/\partial t\right|$$

- **The high potential for inaccuracies in processing the raw acceleration data, as well as the need for a high number of records along the pipeline axis and the associated high installation and operation of a recording array, impede such a solution in extended networks**

- **Commonly PGS is evaluated in a simplified fashion, using PGV:**

$$PGS = PGV/kC$$

- ***C* is a measure of wave propagation velocity and *k* is a correction parameter to account for the maximization of strain as a function of the incidence angle**

Peak Ground Strain (PGS)

- **The selection of *C* and *k* depends on the wave type, the incidence angle and the local soil conditions**

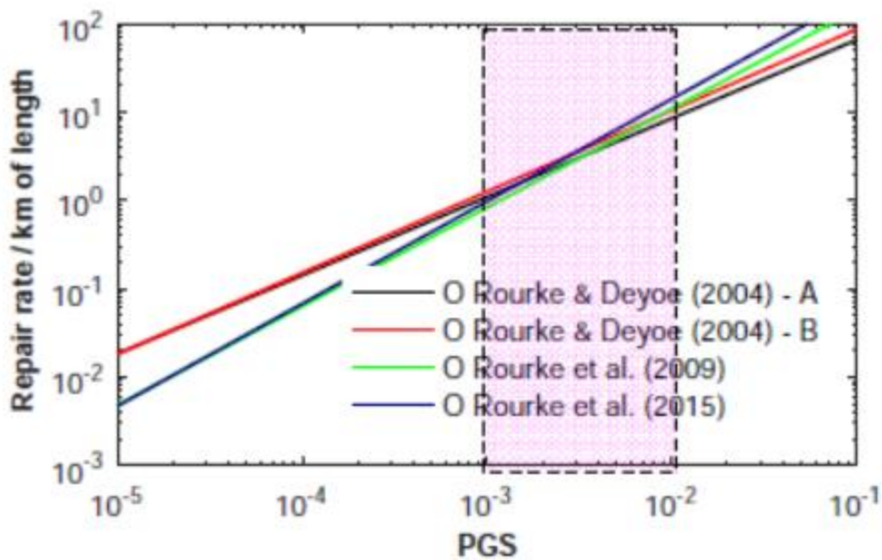
- **Dominant wave type?**
- **S-waves are expected to dominate the response of a pipeline located near the seismic source, while for pipelines located away from the seismic source, surface Rayleigh waves are manifesting the response**

- **Significant deviations in the definition of the above parameters in the relevant guidelines and codes (e.g. ALA 2001, Eurocode 8 2006, O'Rourke & Liu, 1999)**

Peak Ground Strain (PGS)

- **Lateral soil heterogeneities, irregular topography (e.g. variable bedrock depth, hills, canyons, slops) and incoherence and spatial variability of ground motion complicate further the evaluation of εg becomes**

- **Despite the general better correlation of various εg-based fragility relations, compared to PGA- and PGV- based fragility relations, noticeable deviations are still observed**



PGV^2/PGA

- PGV^2/PGA was proposed by Pineda and Ordaz (2007) as a potential IM for seismic assessment of buried pipelines in soft soils
- Dimensionally, this metric corresponds to displacement
- The parameter can be estimated using shake maps or GMPE for PGA and PGV
- Limited verification, since its efficiency was investigated only in the case of the seismic performance of the water supply system of Mexico City during the 1985 Michoacán earthquake

Arias Intensity (I_a)

- **Arias intensity I_a may be considered as a potential IM for the characterization of the structural performance of pipelines, since it embodies both the amplitude and duration characteristics of ground motion**

- **Hwang et al. (2004) reported a good correlation between the observed damages of the gas network of Taichung City during the 1999 Chi-Chi earthquake and the Arias Intensity**

- **However, the computation of Arias Intensity requires a significant number of records of acceleration time histories along the axis of pipeline**

Spectral Acceleration (SA) and Spectral Intensity (SI)

- **O'Rourke et al. (1998) and Hwang et al. (2004) examined the efficiency of spectral acceleration (SA) and spectral intensity (SI) as IMs for embedded pipelines, revealing very poor correlations with the repair rates**

- **These poor correlations are actually expected, since both IM refer to the inertial response of elastic single degree of freedom oscillators, the seismic response of which is highly distinct compared to the one of embedded pipelines**

Conclusions

- **Earthquake-induced ground deformations can trigger different damage modes on continuous embedded pipelines, which can have different consequences on the structural integrity and servicability of the pipeline**

- **The available fragility functions do not cover all NG pipeline typologies and do not distinguish between various damage modes and associated consequences**

- **One of the main issues that prevent the definition of the optimum IM for a quantitative seismic assessment of NG pipelines is the lack of evidence, regarding the efficiency of various IM to correlate with particular damage modes of pipelines**