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EXCHANGE-RISK: EXPERIMENTAL & COMPUTATIONAL HYBRID ASSESSMENT OF NATURAL GAS PIPELINES EXPOSED TO SEISMIC RISK

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ABSTRACT

Historically, a number of major catastrophic earthquakes have resulted in a real loss of life and property world-wide. During the last decades, in particular, the overall exposure to seismic risk has increased not only due to the higher population density but also due to the more challenging construction methods and the multilayered connection between the various urban socio-economic activities. Within this complex built environment, the energy transportation systems, despite their structural simplicity, are seemingly one of the weakest links in terms of seismic safety. Currently, energy production, preservation and safe transportation is one of the top priorities. This demands the need to eliminate the probability of occurrence of a potential seismically induced failure (i.e., related to explosion, fire, leakage etc) that would not only have devastating environmental impact in the affected areas, but could also cause operation disruptions with equally significant socio-economic consequences throughout Europe. EXCHANGE-Risk is an Intersectoral/International, Research and Innovation transfer scheme between academia and the industry in Europe and North America focusing on mitigating Seismic Risk of buried steel pipeline Networks subjected to ground-imposed permanent and co-seismic deformations. This paper discusses the challenges addressed by EXCHANGE-Risk and the recent advancements made in this topic. It also paves the road for further discussion on the methodologies, experiments and tools that need to be developed to mitigate seismic risk of natural gas pipelines at a European level and beyond.

Keywords: Natural Gas Pipelines; Buried Infrastructure; Seismic Risk; Seismic Resilience

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1. INTRODUCTION

During the last two decades, Natural Gas (NG) has become one of the essential components in the energy supply of the 28 member-state European Union (EU), constituting one quarter of primary energy supply and contributing significantly to electricity generation, heating, feedstock for industry and fuel for transportation. As the European Union is currently the world's largest importer (11 trillion cubic feet in 2012), the smooth and safe production, preservation and transportation of natural gas, is one of its top priorities. Such is the need for undisruptive supply in natural gas, that EU has defined specific policies for identifying threshold situations that shall trigger alert and immediate corrective actions to be taken by both the affected Member States and the Union as a whole. As a result, the Directive 2004/67/EC of 2004, concerning measures to safeguard security of natural gas supplies, was transformed in 2010 into the No 994/2010 Regulation (EU Official Journal, 2010) of the European Parliament to define rules, criteria and measures that ensure undisruptive natural supply to the Union. The performance criterion set is that in the event of a disruption of the single largest gas infrastructure, the capacity of the remaining infrastructure, will be able to satisfy total gas demand of the calculated area during a day of exceptionally high gas demand defined with a probability of once in 20 years. This is a high standard approach, significantly more strict compared to the initial alert level of 2004 that set the Major Supply Disruption (MSD) threshold level for Community response at the loss of 20% of gas imports from third countries for at least 8 weeks (Commission of the European Communities, 2009). In the light of the above strategic decisions, it is interesting to notice that the official EU policy is traditionally focused on measures to satisfy the target demand to supply ratios (by keeping them higher than 1.0) solely on the basis of risk scenarios associated with weather, geopolitical issues and human activity. This is clearly reflected on Article 9 of the No 994/2010 Regulation where the potential risks are only identified as the "failure of the main transmission infrastructures, storages or LNG terminals, and disruption of supplies from third country suppliers, taking into account the history, probability, season, frequency and duration of their occurrence as well as, where appropriate, geopolitical risks".

2. SEISMIC RISK OF NATURAL GAS PIPELINES: A SYSTEMIC NATURAL THREAT

Notwithstanding the pragmatic approach of the EU policy on energy sufficiency it is clear that the present approach is assessing risk on a purely geopolitical and financial basis. The reality is, however, that pipeline networks are extensive, interconnected and interdependent constructions that are equally, if not more, exposed to natural hazards. Given that the natural gas pipelines (and oil pipelines) are often buried below ground or submerged to cross the sea, they might be statistically less affected by weather-related phenomena. Nevertheless, in areas of significant *seismic hazard*, they are exposed to potentially detrimental, earthquake-induced deformation demands, caused by wave propagation, active faulting (Joshi et al., 2011; Karamitros et al., 2007), slope instability (Kaynia et al., 2014), soil liquefaction and soil-pipeline interaction (Datta, 1999). The comparison of the present natural gas network in the European Union with the historical earthquakes in Europe (Figure 1) reveals that the areas of overlapping are not marginal. On the contrary, it is seen that most of the importing gates of natural gas to the E.U. are associated to either very high (Italy, Greece, Turkey) or significant seismicity. An additional aspect of the problem is that both offshore and onshore pipelines, despite their structural simplicity, present high *vulnerability* (i.e., probability of pipeline failure for a given intensity measure (Wijewickreme, et al., 2005)) to the aforementioned earthquake-related geohazards (Psarropoulos et al., 2013). In fact, a moderate earthquake, which may cause only minor damage to residential buildings, can easily lead to a local but critical failure within a pipeline network. The potential failure of pipelines may also have a disproportional direct and indirect socio-economic *impact* well beyond the affected area. As there are no political boundaries in natural disasters, consequences in one region can propagate to affect millions of people, the cost of natural gas and the economy as a whole. Financial direct cost of repair may also range from hundreds of thousands to millions of euros. Most importantly, a pipeline failure (i.e., related to explosion, fire, or leakage) may have devastating environmental impact at the vicinity of the incident. The example of the Hyogo-Ken Nanbu earthquake of 1995 in Japan is indicative: gas leakage from buried pipelines occurred at 234 different places and generated fires at more than 531 different spots. Presently, there is a number of safety systems, including line-break detection systems and automated valve controls designed for a "fail to close" condition, however, their operation during a strong earthquake, is not validated, is not guaranteed and it is in any case conditioned to the knowledge of seismic hazard along the pipeline and the reliable estimate of the imposed deformations.

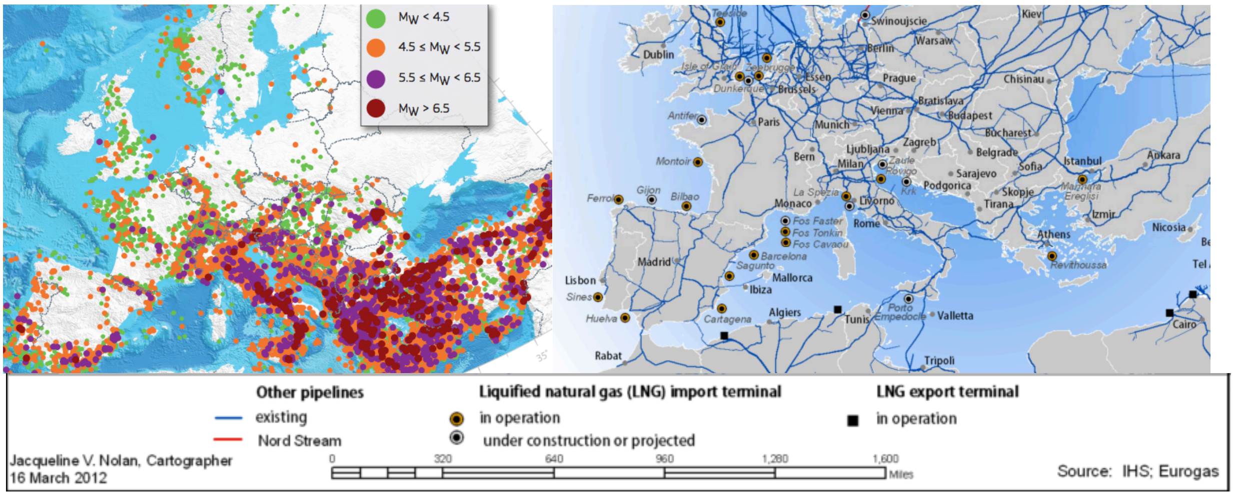


Figure 2: Historical earthquakes in Europe between 1000-2007 (left) (Giardini et al., 2013). European Natural Gas Infrastructure (right) (Ratner et al., 2013).

3. CHALLENGES

In addressing the reliable assessment of seismic risk of natural gas pipelines, several challenges have to be addressed from legislative, research and industrial perspectives.

3.1 Design guidelines for construction and assessment of natural gas pipelines is seismic areas

Apart from the lack of a comprehensive strategy integrating man-made and natural hazards, seismic design of extended pipelines is also lacking a detailed legislative framework. The only design document currently available in the E.U. is Part 4 of Eurocode 8, Chapter 6 on “Silos, tanks and pipelines”. Different provisions apply for above-ground and buried pipelines, the main distinction being the effect of inertia forces which is neglected in the latter case, however, there is no procedure on mitigation of seismic risk of NG pipelines and specifically providing means for quick inspection and rehabilitation in case of an earthquake event. Moreover, the guidelines are too general while the methodology to predict wave-induced earthquake loading is provided in a short informative Annex based on Newmark’s method (Newmark, 1967), thus providing an approximate, but valuable estimate of earthquake demand.

3.2 Spatially variable earthquake induced displacements along the pipeline axis

In contrast to the simplified wave propagation method prescribed in Eurocode 8, extensive research work during the last 20 years (Burdette et al., 2008; Sextos, Kappos, & Pitilakis, 2003), that was based on the pioneer work of other consortium partners (e.g. Deodatis, 1996; Deodatis & Shinozuka, 1989), has shown that the dynamics of long structures under asynchronous excitation are associated with entirely different mechanisms of response. From a physical point of view, this phenomenon can be easily visualized by considering that, in case of an extended structure, seismic waves need a finite time to arrive at different points of the construction, while at the same time they are continuously reflected, refracted, and superimposed as they propagate through the soil medium. The result of this complex and stochastic physical procedure is that seismic waves gradually lose their statistical correlation, or else, their coherency. Local site amplifications further modify the incoming wavefield, hence , ground motion excitation along an extended construction varies significantly in terms of its frequency content, phase and amplitude (Der Kiureghian & Neuenhofer, 1992). Notably, these response features may be entirely suppressed using conventional analytical methods. Most importantly, the approximate design expressions provided by Eurocode 8 – Part 2 (CEN, 2005) for addressing the problem for the case of other extended structure (i.e., bridges) for addressing the problem are not only oversimplifying but may be highly misleading (Sextos & Kappos, 2009), while they cannot easily be extrapolated for the case of pipelines. Numerous other researchers (e.g. Lou & Zerva, 2005), however, the above findings are not yet reflected in the present state of the European Norms. Similarly, the U.S. design codes for pipelines do not prescribe any other means to consider the stochastic nature of earthquake input.

3.3 Soil-pipeline interaction

Part 4 of Eurocode 8 defines two distinct types of soil-pipe interaction; (a) inertial and (b) kinematic interaction, the first being neglected given that the pipeline is embedded in the soil, while there is no explicit guidance for the latter. Most importantly, no rules or methods are prescribed to account for soil compliance even though since the 70's, both small- and large-scale experiments were conducted for this purpose. The response of pipes buried in sand under lateral (Almahakeri et al., 2014; Trautmann & O'Rourke, 1985) and axial (El Hmadi & O'Rourke, 1988) monotonic loading was investigated with different combinations of pipeline's diameter (D) and embedment depth (H) thus covering a wide range of the burial depth ratio (H/D). In some cases, oblique loadings were also examined (Guo, 2005; Nyman, 1984). These studies resulted in different, usually bi-linear, force-displacement relationships, similar to those adopted in the U.S. (American Lifelines Alliance (ALA), 2001). In parallel to the experimental methods, numerical methods were also developed. Common ground of these studies is the consideration of monotonic loading and the assumption of uniform soil conditions along pipeline's length. In reality however, natural gas (NG) pipelines are cyclically excited and, since they extend over large areas, soil conditions along their route are expected to be different. Pioneer studies (Hindy & Novak, 1979) indicated important pipeline stress concentration at the boundary of two different soils. In addition, considering only vertically propagating seismic waves, both laboratory tests (Nishio, 1989) and numerical studies using FEM and FEM/BEM (Ando et al., 1992; Liu & O'Rourke, 1997) proved local strains to be concentrated at points where the pipeline crosses soils with different properties or at regions with inclined soil-rock interface. In this context, the challenge is to develop reliable cyclic force-deformation relationships for (a) axial, (b) transverse horizontal and (c) transverse vertical springs, taking into account the potential effect of the trench wherein the pipelines are buried.

3.4 Experimentally verified modes of failure

Damage patterns in pipelines are of different form and largely dependent on a number of features related to the properties of the material and the joint detailing: tension cracks, compression cracks, local buckling, beam buckling, axial pull-out, crushing of bell end, crushing of spigot joints, circumferential failure and flexural failure; all resulting from co-seismic deformation, faulting and liquefaction. Over the years, researchers have attempted to understand pipeline strength and nonlinear behavior, most frequently numerically (Abolmaali & Kararam, 2013; Joshi et al., 2011; Jung & Zhang, 2011; Vazouras et al., 2010, 2012) or analytically (Karamitros et al., 2007; Karamitros et al., 2011). Various tests were also performed as mentioned in order to account for the static stiffness of the pile-soil system. Researchers have further addressed, based on primarily centrifuge experiments, the influence of fault type, the influence of angle between the pipe and fault for strike-slip faults inducing net axial tension in the pipe and the differences in the pipe behavior for strike-slip faulting which induces net axial compression in the pipe (Abdoun et al., 2009; Almahakeri et al., 2014; Ha et al., 2008). However still, there has been little physical modeling and tests with the specific aim to verify the numerical modeling approaches and assumptions. There are two major challenges involved in the experimental testing of soil-pipeline systems: One is the compliance of the surrounding soil and the large dimensions of the problem. This has been long addressed in other extended systems, such as bridges through the concept of pseudo-dynamic (PSD) testing in which a part of the structure can be physically tested while the rest (the numerical part) is numerically modeled with finite elements, using an appropriate time-integration algorithm for the equations of motion. An extension of this approach is multi-site 'Hybrid Simulation' initiated in the United States and Japan (Kwon et al., 2005), wherein different experimental facilities, that are remotely located simultaneously test multiple sub-components. Recently, an intercontinental hybrid experiment was performed for the case of an extended bridge (Bousias et al., 2017). A limitation, however, in extending this concept to the case of soil-pipeline systems is that that the latter consists a distributed mass system for which the pseudo-dynamic testing method is not unconditionally accurate, hence similar experiments are very limited and require justification.

3.5 Fragility of natural gas pipelines

A large number of the so-called fragility curves relating the probabilistic vulnerability of specific structural systems to seismic intensity is currently available both in Europe and the US, primarily for buildings and bridges (Kwon & Elnashai, 2006) some additionally considering soil-structure interaction effects, surface fault rupture (Kim & Shinozuka, 2004) and pre-earthquake strengthening (Padgett & Desroches, 2009). There exist few probabilistic expressions for the anticipated damage of pipelines (Lanzano et al., 2013) due to earthquake loading. Notably, they solely concern local damage (tension cracks; local buckling; beam buckling) without due consideration of the coupling between the spatially variable ground displacements and soil-pipeline interaction that was described previously. Moreover, fragility expressions for the Metering/Regulating stations linking the High Pressure Natural Gas Transmission System to the local Natural Gas Distribution Network are only empirical. Limited is also the work on connectivity performance indicators (serviceability ratio and connectivity loss) and analytical models to predict functionality at Network level. Therefore, analytical study of pipeline vulnerability based on experimental results as well as interaction with the construction and operation companies of Natural Gas Networks is highly desired.

3.6 Pre- and post-earthquake management of seismic risk towards network resilience

Seismic loss scenarios have long been developed for many European areas primarily focusing on building damage with some applications to lifelines (Pitilakis, 2007). Pioneer work has been performed in terms of seismic risk of transportation networks wherein methodologies, software and special tools have been developed world-wide based on network analysis (Augusti et al., 1998; Esposito et al., 2015), seismic hazard assessment, vulnerability assessment for each network component and estimation of the direct and indirect earthquake loss. Due to the spatial distribution of the data available and the results obtained, a Geographical Information System is typically implemented (Sextos et al., 2008). A key tool in the US has been the development of HAZUS methodology (FEMA-NIBS 2003) and the associated software, which includes a module dealing with Direct Physical Damage to Lifelines - Transportation Systems. HAZUS provides estimates of physical damage, as well as functionality, of the different components of the roadway network, but, unlike REDARS, it does not address interdependence of components on overall system functionality and does not perform network analysis. In its latest version (2004), HAZUS supports consideration of multiple hazard sources (i.e., floods, tornados, earthquakes). Other probabilistic approaches have also been developed (Stergiou & Kiremidjian, 2008) that take into account the impact of the risk of individual network components on the overall post-earthquake system loss and functionality. According to HAZUS, lifelines are divided into the two major categories of transportation and utility systems. In the HAZUS model, it is assumed that pipeline damages subjected to earthquakes are completely independent from the pipeline size, class, and mechanical specifications.

4. CURRENT FINDINGS IN THE FRAMEWORK OF EXCHANGE-RISK RESEARCH

4.1 Main objectives

EXCHANGE-Risk is an Intersectoral and International, Research and Innovation transfer scheme between academia and the industry in Europe and North America focusing on mitigating Seismic Risk of buried steel pipeline Networks that are subjected to earthquake-imposed permanent deformations. It also aims in developing a (nearly real time) Decision Support System for the Rapid Pipeline Recovery to minimize the time required for inspection and rehabilitation in case of a major earthquake. EXCHANGE-Risk involves hybrid experimental and numerical work of the soil-pipeline system at a pipe, pipeline and network level integrated with innovative technologies for rapid pipe inspection aiming to:

- develop a comprehensive, probabilistic methodology and state-of-the-art research knowledge for assessing the seismic vulnerability and mitigating the associated risk of natural gas pipelines, inclusive of its direct and indirect (socio-economic) consequences,

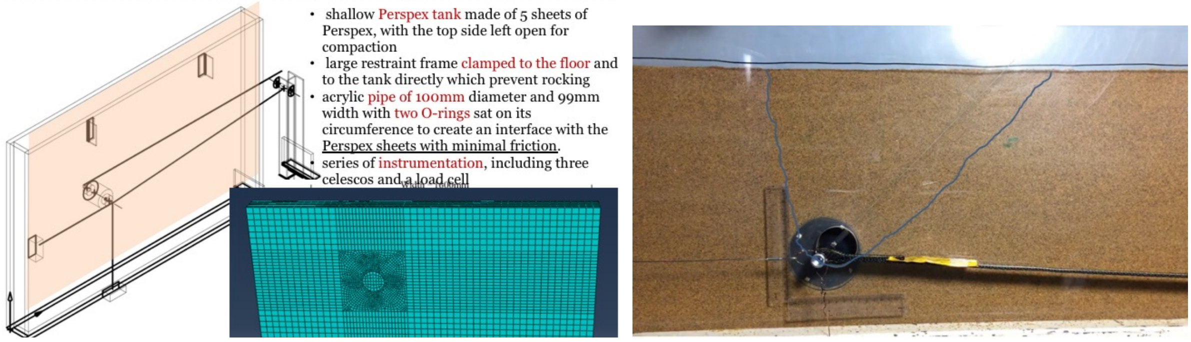
- perform geographically distributed hybrid and/or sub-structured experiments of a soil-supported pipeline, considering peaks of seismic demand along its length that occur due to the spatially variable nature of soils and earthquake ground motions
- develop software to integrate novel hardware technologies for (nearly) real-time identification of the network components with the highest probability of post-hazard failure, their rapid inspection and the ultimate improvement of gas network resilience,
- revisit the existing legislative framework in terms of design, maintenance and rehabilitation of NG pipelines, as well as decision-making towards mitigating the Major Supply Disruption Risk.

4.2 Key research findings

At first, detailed mapping of the emerging research needs for the research and professional community on the analysis, assessment, design and management of natural gas pipeline networks has been performed (Psyrras & Sextos, 2018). Progress made in all front of the EXCHANGE-Risk project are briefly presented in the following.

4.2.1 Experimental and numerical investigation of soil-pipe interaction

In light of the geographically distributed hybrid test that is planned for year 3 of the project experimental framework has been initiated in the Universities of Bristol, Toronto and Patras. First, an experimental setup was constructed at the University of Bristol to study the in-plane stiffness of the soil-pipe system (Crewe et al., 2018) confirming good agreement with respect to numerical analyses and previous findings from the literature (Figures 2 and 3). A complementary setup has also been developed in Toronto to consider the cyclic nature of earthquake loading (Figure 4). Currently, a new experimental configuration is setup at the University of Bristol involving a stacked-layer shear box to test the numerically identified modes of failure of soil-pipe systems under earthquake loading (Figure 5). Universities of Naples and Toronto further developed a demonstration-sized low-power actuator and wrote the necessary software for the controller. This device is able to interface with the UT-SIM hybrid simulation platform and perform small-scale tests on simplified physical specimens of soils and pipelines. The purpose of the device is to provide a testbed for the software implementation of the simulation before moving into the lab and connecting the controllers to hydraulic actuators. Furthermore, it can facilitate coordinated development of the control and network communication code among partner institutions, since similar devices can be assembled at different locations at low cost (Figure 6).



- shallow Perspex tank made of 5 sheets of Perspex, with the top side left open for compaction
- large restraint frame clamped to the floor and to the tank directly which prevent rocking
- acrylic pipe of 100mm diameter and 99mm width with two O-rings sat on its circumference to create an interface with the Perspex sheets with minimal friction.
- series of instrumentation, including three celescos and a load cell

Figure 1: Experimental setup to study the soil-pipeline static stiffness (Crewe et al., 2018).

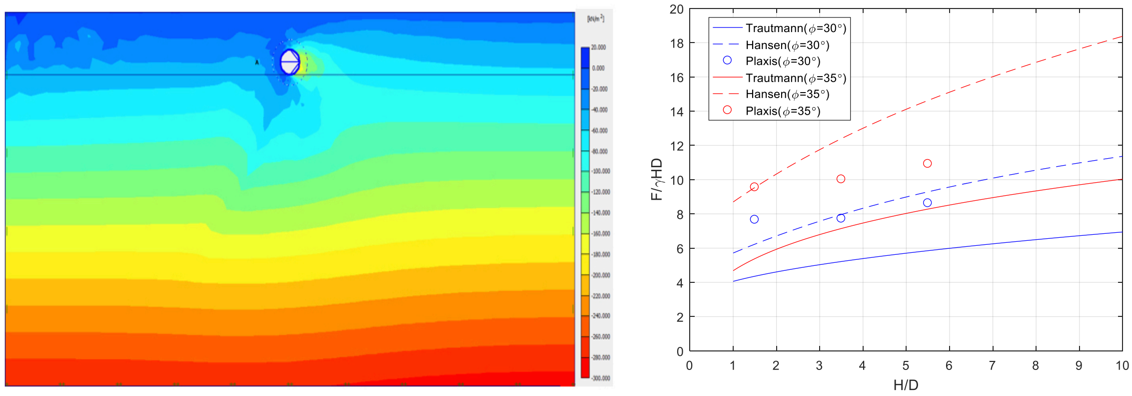


Figure 2: Numerical analysis (left) under lateral loading and indicative results in comparison to previous research findings (N_{qh} vs H/D curves, bottom)

Given the computational demand associated with numerical modeling of the soil-pipeline system with 3D finite elements or coupled BEM/FEM that is required in order to compute the seismic demand on the pipeline, several lower order spring-based models have been developed including: a preliminary Finite Element model coupled with a Boundary element method implementation and is able to study the effects of axial, transverse horizontal and vertical loading (Stutz & Wuttke, 2018), advanced nonlinear mechanical models combining springs, dashpots and sliders (Markou & Kaynia, 2018; Markou & Manolis, 2016a, 2016b; Markou et al., 2018) and a novel model based on Generalized Beam Theory that matches successfully the linear response of the corresponding shell model (Bianco, Koenke, Habtemariam, & Zabel, 2018). The above models will be assessed and compared before identifying the most reliable one to be used in the framework of the experiment involving problem sub-structuring and coupling between numerical and physically tested components of the soil-pipe system.

4.2.2 Pipeline seismic demand due to spatially variable earthquake ground motion

To account for the way in which seismic demand varies along a gas pipeline in case of uniform and non-uniform soil profiles, both a 2D linear viscoelastic and a linear-equivalent site response models were developed for two site scenarios to predict the anticipated range of seismic demand in terms of longitudinal strains for input motions of various intensities and frequency content. The influence of key problem parameters is examined and the most unfavourable ground deformation cases are identified (Papadopoulos et al., 2017). In the second stage of analysis, the critical in-plane soil displacement field is imposed in a quasi-static manner on a long cylindrical shell model of the pipeline through a near-field trench-like continuum soil model, and the performance of the buried pipeline is assessed. Peak nonlinear longitudinal strains due to strong motion can be as much as two orders of magnitude larger than their linear counterparts as a result of the severe moduli degradation.

Figure 4: Overview of the experimental setup at the University of Toronto to study the soil-pipeline system static stiffness and detail of the soil-pipe box to be tested (bottom).

As shown in Figure 7 (Psyrras et al., 2018), it is demonstrated that the seismic vibrations of certain inhomogeneous sites can generate appreciable axial stress concentration in the critically affected pipeline segment near the discontinuity, enough to trigger coupled buckling modes in the plastic range (Figure 8). This behavior is found to be controlled by strong axial load-moment interaction and is not reflected in code-prescribed limit states.

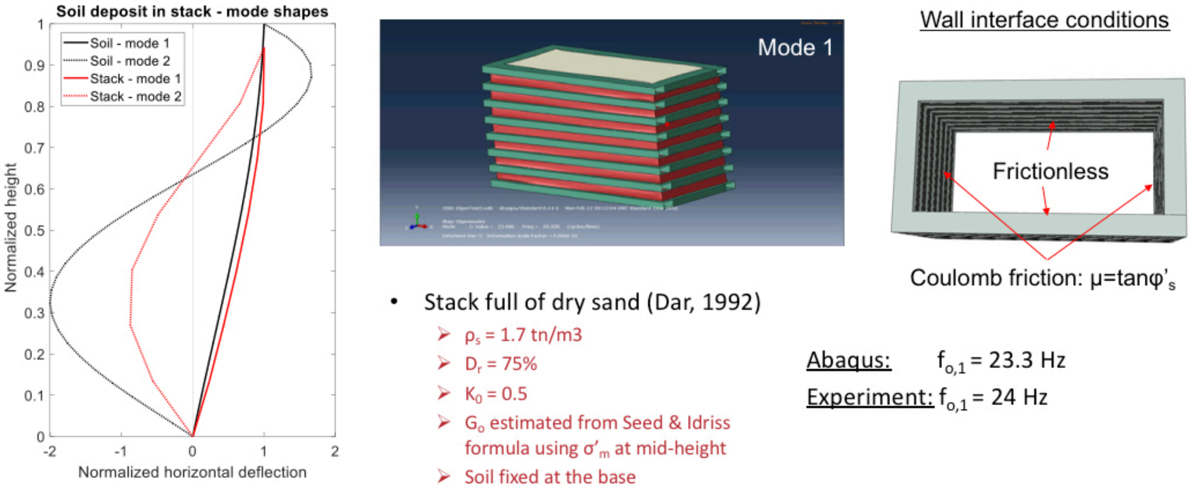


Figure 3: Preliminary design of the shear stack for testing soil-pipe interaction under dynamic loading.

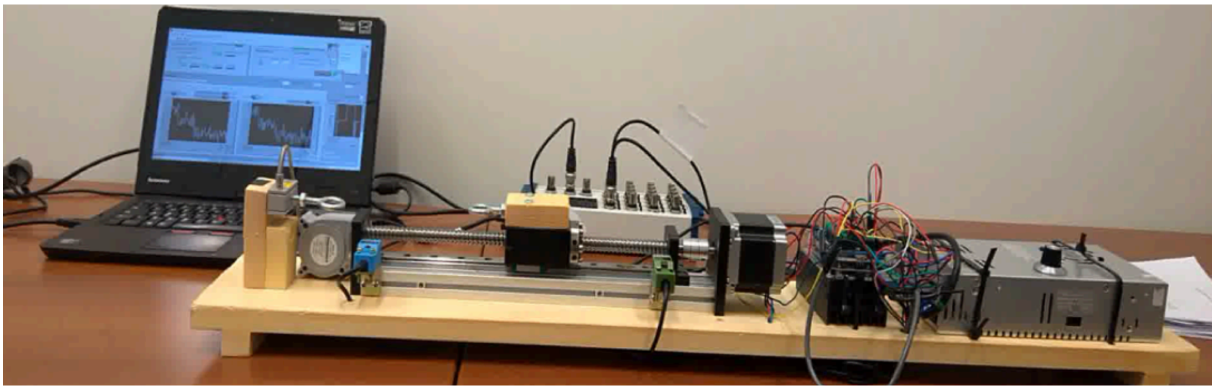


Figure 6: Small size low-power actuator able to interface with the UT-SIM hybrid simulation platform and perform small-scale experimentation on simplified physical specimens.

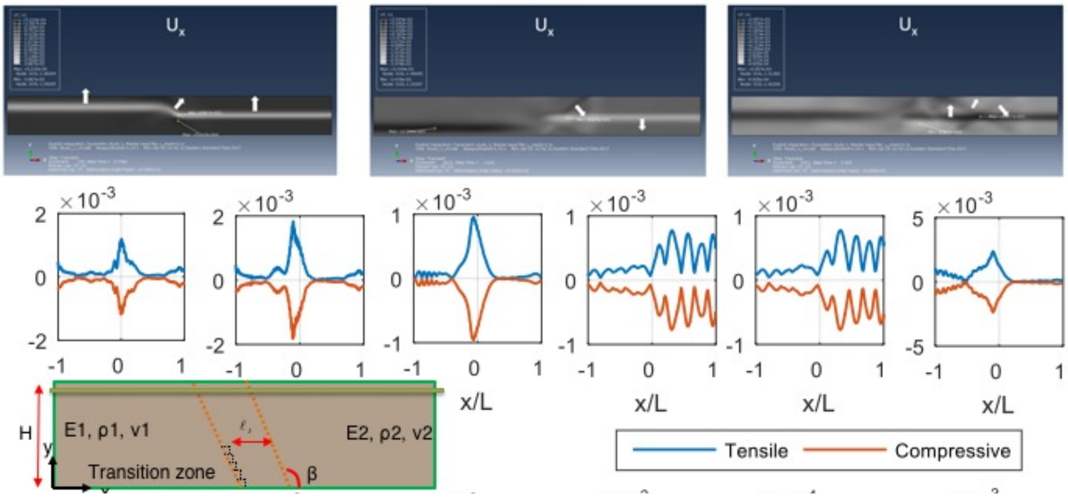


Figure 7: Effect of spatially varying soil conditions on ground motion and pipeline axial seismic demand (Psyrras et al, 2017)

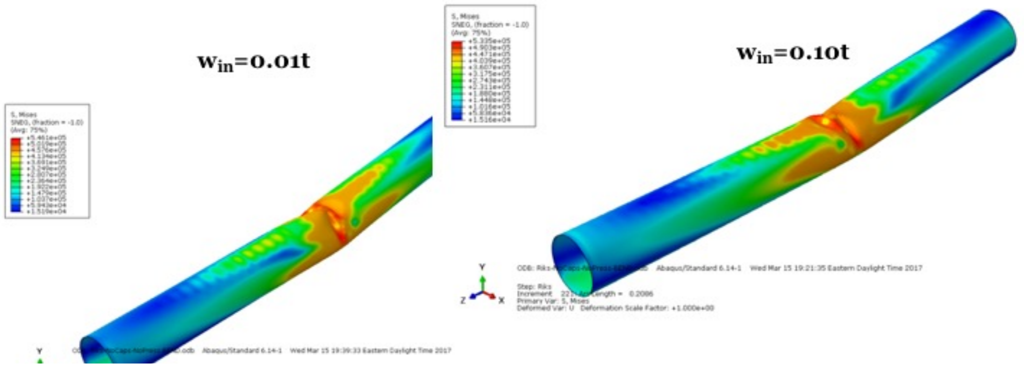


Figure 8: Sample results of pipeline buckling under axial compression for different degrees of imperfection.

4.2.3 Probabilistic assessment of pipeline failure at a component and network level

The fragility of the soil-pipe system for different damage modes of failure has been studied based on the patterns reported in the literature (Psyrras & Sextos, 2018) and the efficiency of various seismic Intensity Measures (IM) for the structural assessment of gas pipelines under transient ground shaking. A new methodology has also been developed (De Risi et al., 2018) to assess the risk of a gas pipeline infrastructure at regional level in the aftermath of a seismic event. Once earthquake characteristics, such as magnitude and epicentre, are known, seismic intensity measures, such as peak ground acceleration (PGA) and peak ground velocity (PGV), are estimated at the location of each pipe through a simulation-based procedure. The potential updating from real-time data coming from accelerometric stations is considered. These IMs are then used to study the cascading landslide and liquefaction hazards providing a hybrid empirical-mechanical-based estimation of permanent ground displacements (PGD). With the aid of literature damage and fragility functions, loss figures and damage maps are derived as decision-support tools for network managers and stakeholders. Losses provide a preliminary estimation of repair costs, while damage maps support the prioritisation of inspections in the aftermath of the event. The particular risk methodology is a novel combination of consolidated approaches as different cross-correlation models between PGA and PGV are included and, secondly, a new three-phase back-to-back geotechnical approach is provided for both landslide and liquefaction, representing (i) the susceptibility, (ii) the triggering, and (iii) the PGD estimation phases. To demonstrate the efficiency of the method, the 1976 Friuli earthquake and the high-pressure gas network of North-East Italy are assumed as test-bed scenario for the risk methodology aimed at emphasising pros and cons of the different alternative options investigated (Figure 9). The characteristics of strong ground motion recorded in nearby areas have also been systematically studied (Iervolino, Baltzopoulos, Chioccarelli, & Suzuki, 2017) and will be used as a benchmark case for analyses performed in the framework of EXCHANGE-Risk.

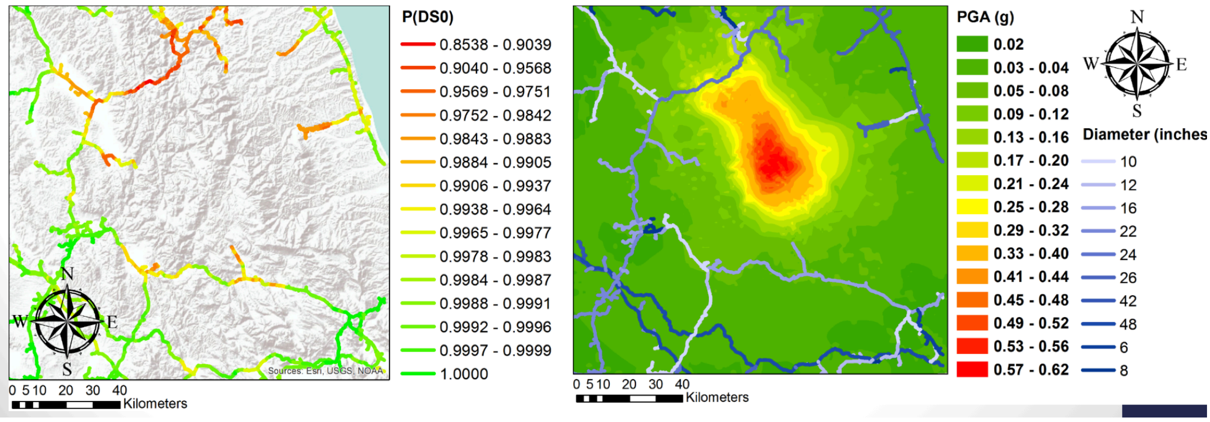


Figure 9: Sample results of spatial correlation of PGA with the corresponding probability to exceed Damage State 0 in the area of Central Italy (De Risi et al., 2018).

5. CONCLUSIONS

This paper presents the challenges associated with a reliable assessment and mitigation of seismic risk of natural gas pipelines. It discusses the existing literature, the emerging research needs and the objectives of the H2020 research project EXCHANGE-Risk, while presenting the progress made and the key research findings up to the project mid-term. Some results are preliminary and aim to facilitate the preparation of the final experimental campaign that involves geographically distributed testing among the partners. In most case, they further contribute to the understanding of the way in which the pipeline and the surrounding soil interact under seismic loading including complex material and geometrical nonlinearities and large-scale site response that may trigger localized seismic demand peaks along the pipeline. The fragility of the soil-pipe system is studied at both a component (i.e., pipe segment) and network level and tools are developed for risk assessment and efficient management of the network. Further research is currently performed through which hazard, fragility and exposure are to be convoluted and informed by experimental testing and refined numerical analysis.

6. ACKNOWLEDGMENTS

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