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STRUCTURAL HEALTH MONITORING OF BURIED PIPELINES UNDER SEISMIC HAZARD: A REVIEW OF DAMAGE SCENARIOS AND SENSING TECHNIQUES

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ABSTRACT

Damage assessment to lifelines after natural disasters, specifically earthquake events, is primordial for emergency response and rescue work. Post-disaster assessment of damaged buried pipelines is challenging because it requires earthworks, and this challenge increases specifically in urban areas. Several non-destructive techniques (NDT) are currently used for internal and external assessment of pipelines. Most of them need the location of damage to be already known and are not suited to real-time automated health monitoring. In this regard, permanent monitoring platforms based on the use of fiber optics sensors and wireless sensors appear promising for a rapid health assessment of buried pipelines even though challenges related to the harsh mechanical environment and the need of long-term power solution must be properly taken into account. In this paper is reported a review of the approaches currently adopted for the monitoring of buried pipelines under seismic hazard. First, different damage mechanisms that can affect buried pipelines in seismic-prone areas are described. Following a review of the current research efforts toward sensing methods for permanent SHM is reported.

Keywords: Structural health monitoring; Buried pipelines; Seismic hazard

1. INTRODUCTION

Pipelines are widely used for the transportation of fluids for industrial and civil purposes. Potable-water and waste-water pipelines are particularly vulnerable lifelines since their damage can lead to pollution and epidemic outbreaks. To this respect, the possibility to promptly detect damage can greatly enhance the resilience of communities toward natural hazards.

Several non-destructive techniques (NDT) are currently used for internal and external assessment of pipelines: acoustic and ultrasonic emissions, internal inspection using cameras, robotic systems and ultrasonic transducers, eddy current technique and ultrasonic Lamb waves, infrared thermography systems and ground penetrating radar. Most of these methods require human intervention - that adds subjectivity to the process - and the location of damage to be already known. Moreover, these technologies are not appropriate for real-time automated health monitoring particularly of buried pipelines that are usually difficult to reach thus requiring the use of remote sensing techniques. In this regard, permanent monitoring platforms based on the use of fiber optics sensors and wireless sensors appear promising even though challenging due to the harsh mechanical environment and the need for long-term power solution.

In this paper is reported a review of different approaches to damage detection and monitoring of

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buried pipelines under seismic hazard. The different possible damage mechanisms are described and the existing inspection methods are critically discussed. A review of the current research efforts toward permanent real-time Structural Health Monitoring (SHM) systems concludes the article.

G. Lanzano et al. (2014) highlighted that minimal and general provisions are provided by the current codes concerning the seismic behavior of lifelines structures which have predominant one-dimensional development and are often dislocated over wide areas. Particularly, only general principles are provided in Eurocode 8 part 4 (EN 1998-4, 2006) to ensure earthquake protection.

In this paper is reported a review of different approaches to damage detection and monitoring of buried pipelines under seismic hazard. The different possible damage mechanisms are described and the existing inspection methods are critically discussed. A review of the current research efforts toward permanent real-time Structural Health Monitoring (SHM) systems concludes the article.

2. SEISMIC DAMAGE TO BURIED PIPELINES

As noted by Kakderi and Argyroudis (2014), many have documented the damage to **water systems** while facing earthquake events such as in USA (EERI 1990; NRC 1994; Lew et al. 1994; EERI 1995; Schiff 1995), in Japan (Shinozuka 1995; Chung et al. 1996; Shrestha 2001), in New Zealand (Cubrinovski et al. 2010), and in Europe specifically in Turkey (O'Rourke et al. 2000; Tang 2000; Tromans 2004; Alexoudi 2005), in Greece (Alexoudi 2005; Alexoudi et al. 2006), and in Italy (Stewart et al. 2009).

Others have documented the damage to **waste-water systems** while facing earthquake events such as in the USA (EERI 1990; NRC 1994; Lew et al. 1994; EERI 1995; Schiff 1995), in Japan (Shinozuka 1995; Chung et al. 1996; Shrestha 2001; Scawthorn et al. 2006), in New Zealand (Cubrinovski et al. 2010) and Chile (EERI 2010), and in Europe specifically in Turkey (Erdik 2000; Uçkan et al. 2005) and in Greece (Alexoudi 2005).

In the following the factors that lead to damage to buried pipe (both for continuous and segmented and for different materials) during earthquakes are defined.

2.1 Sources of seismic damage to buried pipelines

ALA (2001), Gehl et al. (2014), Eguchi (1987), Lanzano et al. (2013, 2014), and O'Rourke and Liu (1999) among others noted that seismic damage to pipelines can be caused by two main damage mechanisms: transient ground motion induced by seismic wave propagation and permanent ground displacements due to the failure of the surrounding soil. Wave propagation does not induce breaks or ruptures but disturbs a wide area and can generate well-dispersed damage. Some authors (Gehl et al. 2014), refer to it as transient ground deformation due to R-waves and S-waves and measured in terms of Peak Ground Acceleration (PGA) of Velocity (PGV), or strains; spatially its impact is large and distributed.

Permanent ground displacements are mainly due to faulting, landslides, and uplift that, together with the loss of the shear strength due to liquefaction, are among the principal reasons for pipeline failures during earthquakes (Eguchi 1987) and (Hall 1987). Ground displacements can induce deformations of the pipelines with related increases of the stresses. If the strength is exceeded, tension (cracking) or compression (local or global buckling) failures may occur. Consequent damages can be detected either by: a) the direct measure of the strains on the pipelines; b) detecting the leaks that may occur at the damaged locations; or c) detecting changes in the soil surrounding the pipelines. Ground failures are usually measured in terms of permanent ground displacement (PGD). They occur only when specific geotechnical conditions are met, thus they are site dependent and local.

2.2 Types of damage in water and wastewater pipelines

Pipelines could be over the ground or underground i.e. buried. This article is limited to the seismic behavior of buried pipelines.

Potable water and wastewater pipelines are frequently buried for two main reasons: 1) to be protected by the landfill from above ground damaging events due to natural or human accidents; 2) to have the surrounding soil acting as lateral confinement which reduces the effects of the seismic loading. The

average burial depth is about 1 – 2 m, while very large diameter pipes can be buried deeper.
The damage patterns in pipelines are largely dependent on the construction material properties, on the joint type and detailing, on the diameter of the pipes and on similar correlated parameters such as lining thickness and operating pressure (O'Rourke and Liu 1999, Lanzano et al. 2013, Lanzano et al. 2015, ALA 2001, HAZUS – MR4 2004). Damage, herein considered, encompass both structural changes induced by earthquakes both degrading phenomena such as corrosion or fatigue that can weaken the pipelines, modifying their seismic behavior.
Depending on the type of joint used to connect the pipes, pipeline networks are classified as Continuous (CP) or Segmented (SP). Continuous pipelines (CP) have rigid joints, such as in welded steel pipes while Segmented pipelines (SP) consist of pipe segments attached to relatively flexible or weak connections such as bell-and-spigot cast iron piping system (ALA 2001 and Lanzano et al. 2015).
A different behavior occurs for continuous and segmented pipelines (see O'Rourke and Ballantyne (1992)). In the following sections, a short description of the several damage mechanisms for the two typologies of pipelines is reported mainly based on O'Rourke and Liu (1999).

2.2.1 Damage to Continuous pipelines

The main failure modes of continuous buried pipelines, when free of corrosion, are function of the burial depth. The failure mode is a tensile rupture and local buckling when burial depth is greater than one meter, and beam buckling when burial depth is less than one meter.
The *tensile failure* of corrosion-free buried pipelines depends also on the welding technique used for their joints. The performance of the joint welds is listed in a decreasing order: arc welded butt joints, gas welded joints, welded slip joints. For steel pipelines with slip joints, riveted joints or oxy-acetylene/gas welded joints, failure mode depends on the strength of these joints that is lower than that of the pipe materials. Slip joints with an outer weld are more used than inner welds. The joint efficiency of slip joints with an inner weld is often larger than that with an outer weld.
Local buckling or wrinkling involves local instability of the pipe wall that is a common failure mode for steel pipes. It is caused mainly by ground deformation or wave propagation and often leads to circumferential cracking of the pipe wall and leakage.
Beam buckling induces a transverse upward displacement of the pipe. The compressive pipe strains are not large since the relative movement is distributed over a large distance. Therefore beam buckling in ground compression is more desirable than local buckling. This is a serviceability problem since the pipes do not "fail". A pipe buried at a sufficient depth will develop local buckling before beam buckling.

2.2.2 Damage to Segmented pipelines

For segmented pipelines, particularly those with large diameters and relatively thick walls observed seismic failure is most often due to distress at the pipe joints. Sun and Shien (1983) observed that around 80 percent of pipe breaks were associated with joints. M. O'Rourke and Ballantyne (1992) identified six types of damage mechanism to segmented pipelines: pipe segment break, disconnection at Tee, break in union piece, compressive telescoping at joint, blowout at tee, and tensile pull-out at joint.
Axial pull-out, sometimes in combination with relative angular rotation at joints, is a common failure mechanism in areas of tensile ground strain. In areas of compressive ground strain, the crushing of bell and spigot joints is a common mechanism in concrete pipes. For small diameter segmented pipes, circumferential flexural failure close to joints is common in areas of ground curvature.
Axial pull-out: In term of failure criterion, information for the various types of segmented pipes is not as well developed as for continuous pipes. Bouaid and M. O'Rourke (1994) noted that it would appear that a relative axial joint extension of roughly half the total joint depth may be an appropriate failure criterion for many types of segmented pipes.
Crushing of Bell and Spigot joints: Bouaid and M. O'Rourke (1994) stated that joint failure to reinforced concrete cylinder pipes with rubber gasketed joints, can start at either the inner concrete lining or the outer concrete lining. After concrete lining cracks, the critical section then becomes the

welded interface between the steel joint ring and steel pipe cylinder.
Circumferential flexural failure and joint rotation: When a segmented pipeline is subjected to bending induced by lateral permanent ground movement or seismic shaking, the ground curvature is accommodated by some combination of rotation at the joints and flexure in the pipe segments. The relative contribution of these mechanisms depends on the joint rotation and pipe segment flexural stiffnesses.
For cast iron or asbestos cement pipes subject to ground curvature, round flexural cracks in segments are a major failure mode. On the other hand, for concrete pipes subject to ground curvature, cracks typically occur at the bell and spigot ends due in part to the joint ring eccentricity mentioned previously.
Similarly, Lanzano et al. (2014) summarized the most relevant aspects from the structural perspective and damage pattern and combinations of material and joints, in addition to the main transportation fluids used in each structural type. They were mainly divided as follows: for Continuous pipelines CP, the damage pattern were tension cracks, compression cracks, local buckling, beam buckling; for Segmented pipelines SP, the damage pattern was axial pull-out, crushing of bell end, crushing of spigot joints, circumferential failure, and flexural failure.
Moreover, ALA (2001) and HAZUS – MR4 (2004) resumed that damage could be breakage or leakage.
Finally, the rate of corrosion in the metallic pipeline and the effect of aging and the presence of anti-seismic devices are considered to be additional significant issues for performance evaluation (Lanzano et al. 2013; ALA 2001; HAZUS – MR4 2004).

3. SENSING TECHNIQUES FOR MONITORING OF BURIED PIPELINES

Monitoring systems of pipelines in seismic prone regions can have a twofold goal:

1) Give an alert about the occurrence of a seismic event that can enable making informed decisions about the pipeline activity. This may encompass pressure relief in case of exceedance of a predefined safety threshold or the maintenance of the operational level in case the measured intensity of the earthquake does not endanger the safety of the pipeline.
2) Allowing the detection of possible damages induced by earthquakes thus enabling post-earthquake repair interventions.

3.1 Monitored parameters

Monitoring systems as early warning system are usually based on the measure of the Peak Ground accelerations (PGA) at locations close to the pipeline. Following an approach quite common for trains – for example, the Shinkansen in Japan – or nuclear power plants, a threshold value of the PGA is defined to bound the operational range of the structure. If the threshold is exceeded, an alarm is given so that actions can be initiated to protect the system. For pipelines, the action could be a reduction of the operating pressure. The system can as well be used to keep the pipeline under normal operating conditions during small earthquakes based if the PGA stays below the predefined threshold.
The detection of damages in the pipelines requires the measurement of parameters related to the structural behavior of the pipeline itself, of its supports and of the surrounding soil. The parameters usually measured, both directly related to the movement induced by the ground motion, are strains - values and concentrations - or displacements.
Another parameter that is usually measured is temperature since its variations may indicate the presence of leaks originated by pipelines failures (Inaudi et al., 2007; Nikles et al., 2004) or of soil erosions produced by the surrounding soil failure. Leaks induce *a variation of temperature* since the water inside the pipes is usually warmer than the surrounding soil. Erosion of the soil surrounding the pipelines is another source of *variation of temperature* due to the difference of temperature between air and soil and also to the possible ingress of water in the spaces where the soil is eroded.
Therefore the parameters that need to be monitored for pipelines under seismic actions are PGA, PGV, PGD, strains, and temperature.
Another parameter that can be used to detect ruptures in the pipelines is the acceleration recorded on its surface that undergoes sudden changes induced by disturbances of the water flow and pressure due

to ruptures (Nwalozie et al 2014). Similarly, abrupt changes in pressure data can enable the detection of pipelines ruptures due to the negative pressure wave that is generated at the location of the rupture (Misiunas et al. 2005). Damage to the pipes cause variations in water flow parameters (pressure, discharge, and velocity) that can be used as input data to detect failures (Ardakani 2004)
Several sensing solutions have been proposed in the literature and some of them successfully applied to real case studies, for assessing pipeline through the monitoring of the previous parameters. Both periodic - carried out for short time intervals - and permanent monitoring – sensors that continuously record the structural response – can be performed using point or distributed sensors. More details about the several available sensing systems are given in the following sections.

3.2 Periodic Non Destructive sensing

The choice of a periodic sensing is usually performed based on the constitutive material of the pipe.
For **steel buried pipelines** the inspection is mainly achieved by insertion of devices in the pipe interior, such as pigs (Liu 2003), which may contain several types of sensing transducers (Glisic 2014). Examples are magnetic flux leakage (MFL) to detect defects in the pipe wall; remote field eddy current (RFEC) which uses low frequency alternating current (AC) and detects wall damage such as corrosion or cracking (Najafi 2004); ultrasonic transducers which can also be installed on the surface of the pipe (Kobayashi et al., 1999; Rose 1999; Towfighi et al. 2002) and can reliably detect and locate the damage. Moreover gauging tools and cameras can be mounted on the pig (Kennedy 1993) to measure the changes in diameter of the pipe and to locate dents, etc.
Concrete pipelines are divided mainly into gravity pipelines and concrete pressure pipelines.
Gravity pipelines such as sewers are inspected mainly using closed-circuit television (CCTV), which reports visible defects in the pipe (Najafi 2004; Sinha and Fieguth 2006). The sewer scanner and evaluation technology (SSET) is a more sophisticated version of CCTV, which allows 3D reconstructed images. Ultrasonic systems can be used if the interior of a pipeline is accessible (Wirahadikusumah et al. 1998). They can measure the thickness of the pipe and identify cracks but cannot inspect beyond the inner pipe surface, due to high attenuation of the ultrasonic signal (Duran et al. 2002). Focused Electrode Leak Location (FELL) technology and laser-based scanning systems can identify leakage and infiltration points along the pipelines. The robotic driven instrumentation main disadvantage is that it can get stuck in the pipeline during inspections.
Several remote-sensing techniques have been also developed such as the ground penetrating radar (GPR) which is used to detect delaminations in concrete sewers and to examine the bedding of the pipeline (Najafi 2004) or the infrared thermography system (ITS), which captures thermal images of soil altered by leaks caused by the rupture of a pipe (Weil 1998).
In Concrete Pressure Pipes, (CPP) degradation is less dependent on the age and is more due to various external effects (Najafi 2004). Moreover, defects are not immediately visible and thus the failure consequences are severe. CPPs and prestressed concrete pressure pipes PCCP are inspected by Remote Eddy Field Current/Transforming Coupling (REFC/TC) to detect, localize, and quantify broken prestressing wires (Grigg 2006; Najafi 2004), which is an advantage over conventional REFC.
Acoustic emission testing is also used to PCCP by placing acoustic sensors along the pipe that receive the transient noise due to the breaking of the prestressing wires and subsequent slippage of the wire in the pipeline wall.
Most of the presented methods require manual inspectors to deploy the monitoring sensor; which also adds subjectivity to the process. Furthermore, those technologies are not appropriate, and some present great limitations, for real monitoring of the buried pipelines. For these reasons other techniques base on permanent networks of sensors have been proposed and are described in the following section.

3.3 Permanent Real Time sensing

Permanent sensing solutions are also available to assess the pipelines health condition both automatically and on-demand. Glisic (2014) identifies three promising sensing solutions for permanent sensing: a) wireless technologies, b) fiber optic sensors (FOS), and c) large area electronics (LAE).
Wireless technologies have been proposed (Straser and Kiremidjian 1998; Lynch 2002; Spencer et al. 2004; Lynch et al. 2006) to limit the cost of the traditional wired sensing for large structures**.** The

sensors (such as strain gages, accelerometers, acoustic emission, etc.) can communicate with the repository by means of wireless communication, provided an analog-to-digital converter and microcontroller are integrated into the wireless node (Glisic 2014). Wireless technologies face two important challenges which ongoing research trying to overcome: power and high attenuation of the wireless signal in the ground. The first problem can be tackled through on-site power harvesting solutions that can be effective thanks to the low power consumption of the wireless nodes. The attenuation of the signal can be minimized by using appropriate radio frequencies (Kim et al. 2010). In reference (Nwalozie et al. 2014) wireless MEMS (Micro-Electro-Mechanical Systems) sensor networks are proposed to monitor the pipe surface acceleration.

Fiber optic sensing technologies can be classified with respect to the measurement principles: point sensors, long-gauge sensors and distributed sensors (Glisic and Inaudi 2008).

Point sensors such as Extrinsic Fabry-Perot Interferometers (EFPI) and the Fiber Bragg Gratings (FBG) are ideal transducers to monitor the local properties of the material. Another application in Thien et al. (2008) proposes the use of macro-fiber composite (MFC) transducers for real-time structural health monitoring in pipeline systems to detect damage in pipes and joints.

For structural monitoring long-gauge sensors, such as the interferometric low-coherence SOFO sensors, give information on the global behavior of the structure (Inaudi 2000). Applications of this type of sensor are reported in references (Inaudi and Glisic 2005). One of the drawbacks of this technology is connected with their cost that, for some applications, is not justified by the increased performance of functionality enabled by the monitoring system (Inaudi 2000).

Distributed sensors rely on Rayleigh scattering (Posey et al. 2000), Raman scattering (Kikuchi et al. 1988), and Brillouin scattering (Kurashima et al. 1990). These sensors use a sensing cable that is sensitive at every point along its length, replacing thus, a large number of discrete sensors. They are cheaper with respect to the previous long-gage sensors (Glisic 2014).

Strain sensors can be installed and bonded directly to the pipeline (Glisic and Inaudi 2007, Inaudi and Glisic 2010), or embedded in the soil. In the first case, they can measure strains along the pipeline and therefore the bending and axial deformation. If they are embedded in the soil they can reliably detect and localize the movements in the soil that can potentially endanger the pipe; this is simpler and faster than bonding sensors on the pipeline (Glisic and Yao 2012). The greatest advantage of distributed fiber optic sensors is that they are continuous, and consequently, all cross-sections of the pipeline are effectively instrumented (Glisic and Inaudi 2007; Nikles et al. 2004). Applications of this technology to the measurement of strains for buried pipelines health assessment are reported in references (Glisic and Yao 2012, Glisic and Oberste-Ufer 2011, and Glisic et al. 2011, Inaudi and Glisic 2010).

Distributed fiber optic sensor based on Brillouin Optical Time Domain Analysis (BOTDA) have been used to detect changes in buried pipe strain profile caused by pipe bending induced by ground movement (Glisic and Yao 2012).

Distributed fiber optic sensors based on Raman or Brillouin scattering (Inaudi et al. 2008, Ravet et al. 2008, Nikles 2009) allow also the measurement of the temperature profile along the pipe and thus the detection of leaks through the identification of temperature anomalies.

Finally (Lim et al. 2016) reported different applications of BOTDA for pipes monitoring (Bernini et al. (2007), Zou et al. (2004, 2006), Kishida et al. (2005), Gu et al. (2009), Ravet et al. (2006, 2008) and Zhang (2008)).

Large area electronics (LAE) have been introduced to tackle the problems related to the reliable early detection of anomalies (e.g. strain concentrations and cracks) using sparsely spaced sensors. Usually, this is a challenging task at locations even modestly distant from the sensors. LAE is an emerging technology that allows a broad range of electronic devices to be integrated on low-cost plastic sheets (Arias et al. 2010; Someya et al. 2008; Someya et al. 2004; Graz et al. 2009). This wireless sensor network is extremely valuable for large-scale monitoring since it allows monitoring and interrogation over distributed point sensors. Thousands of strain gauges can be fabricated onto a single sheet that is both low in cost and highly conformal (Arias et al. 2010; Glisic and Verma 2011). Hence, multi-functional sensing sheets for monitoring strain, temperature, corrosion, pressure, etc. can be created by proper integration techniques. The main challenges of LAE sensors are the power supply and their durable installation at characteristic locations along the pipelines (Glisic 2014). Potential solutions based on energy harvesting through piezoelectric and thermoelectric devices along with thin-film batteries and energy-storage super-capacitors are being investigated (Chen et al. 2010, Glisic and

Verma 2011).
Finally Glisik (2014) noted that innovative solutions are being developed such as: first the sensing skins based on carbon nanotubes (Loh et al. 2009) for 2D strain field monitoring, which provides a 2D mapping of damage, strain field assessment, and detect corrosion (Loh et al. 2007), and it is interfaced using wireless nodes (Pyo et al. 2011). Second, the use of multi-functional materials with self-sensing properties; the electrical properties of cementitious materials can be used to detect and locate defects such as crack (Chung 2003; Lynch and Hou 2005). Successful developments and large-scale implementation of those two technologies can transform an entire pipeline into a sensor.

4. CONCLUSIONS

This article aims to discuss Structural health monitoring (SHM) of buried water and wastewater pipelines under seismic hazard. The different types of damage induced by earthquakes are briefly outlined and the parameters enabling their detection shortly discussed.
Several sensing techniques have been developed and applied to the monitoring of buried pipelines. Wireless sensors, fiber optics, and large area electronic sensing systems appear the most promising for this type of applications.

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