Earthquake and earth movement monitoring: the possibility to use Natural Gas distribution infrastructure

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Abstract: The recent earthquake occurred in central Italy (Magnitude of 6.5) has caused lot of deaths and injuries and several damages to buildings and other infrastructures. As for previous events (L'Aquila in the 2009 and Emilia Romagna in the 2012) experts agree that monitoring should be performed to control earth movement and to be able to identify dangerous situations. "Casa Italia" national program foresees large investments to improve prevention against earthquake events. The installation of monitoring devices on buried pipelines is proposed in the paper as a possible solution for earthquakes and, more in general, earth movements; in fact, a high density of buried pipelines is present in the territory so pipeline monitoring coincides also to ground condition control. The solution shown in the paper ensures the respect of two primary objectives: i) the control of lifelines condition to define cost – effective maintenance programs and ii) the monitoring of earth movement to ensure the execution of emergency plans.

The paper is divided into two parts: in the first one a review of hazard and of interactions between buried pipelines and soil is presented; in the second part requirements and possible critical issues for the implementation of monitoring devices are presented.

Keywords: Natural Gas Safety, Buried Pipelines, Earth Movement, Monitoring.

1. Introduction

In recent years several earthquakes occurred in Italy causing injuries, fatalities and economic damages to infrastructures and lifeline systems that should be available for post-earthquake emergency plans. The loss of primary services, as natural gas, water and electricity, makes more complex safety and restoring operations and increase the risk of secondary events, as natural gas fires (O' Rourke, 1996). The national program called "Casa Italia" has been promoted by the Italian government to improve the overall safety performance through the realization of preventive actions which will be financed to identify preventive and maintenance plans against natural events. In fact, if compared with emergency plans, preventive programs are more complicated to be correctly designed and effectively actuated. In the case of natural events, especially for earthquake and landslide, several parameters should be acquired and analyzed to identify the correct method to detect a dangerous condition. Therefore, a dedicated monitoring system should be designed and installed to receive relevant data and send them to a centralized data center.

Several monitoring systems have been implemented in the past to control earth movement as described by (Pasuto et al., 2000). Extensometric transmitter devices are characterized by some issues due to the high soil movement that may cause complicated maintenance operations as cable tensioning operations, cable power supply repair and inclination conditions restoration. Other type of instrumentation as automatic topographic system (like motorized theodolites and retroreflectors targets, Casagrande piezometric cells, deep seated steel wire extensometers, inclinometers) can guarantee reliable results only if sensors are installed in a meaningful position and if monitoring parameters (i.e. time control frequency and thresholds) are correctly selected.

In (Corominas et al., 2000) borehole wire extensometers are analyzed, achieving easy installation and low cost, but in case of superficial landslide measurements they present some errors respect to real ground movement. In the work of (Casagli et al., 2003) a portable linear Synthetic Aperture Radar (SAR) device which doesn't need additional target to be installed in the controlled zone is investigated. In (Gili et al., 2000) a Global Positioning System (GPS) is proposed and compared with cable extensometers and inclinometers. GPS is a radio navigation timing and positioning system that ensures three axis soil movement measurement with a precision that can reach 5 to 10 mm; GPS systems use receivers, that are installed in the zone to be monitored, and orbiting satellites that send signals which is captured by receivers; high precision is reachable and comparable price has been evaluated respect to traditional systems. In case of high precision request a Real Time Kinematic (RTK) technique should be used but monitoring distances should be maintained within 10 km to reduce measuring errors.

In (Garcia et al., 2010) high resolution tiltmeters are used to measure the internal deformation of a landslide body. In (Pellicani et al., 2017) a satellite Interferometric Synthetic Aperture Radar (InSAR) is used for monitoring the instability of ground due to landslides in Carlantino (Italy). In (Intrieri et al., 2012) a monitoring system approach is defined for the control of a rockslide in Torgiovannetto (Italy).

However, it must be highlighted that ground monitoring could be useful not only for earth movement analysis but also for the preventive identification of faults therefore of earthquake occurrence.

The possibility to monitor all Italian territory wherein earthquake or landslide risk is present meets some issues due to the extension of the area to be controlled. In fact, as reported by the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA) in the 2015 the 88.3 % of the Italian cities and village can be subject to landslide, earthquakes and floods with a total amount of 47.747 km^2 of hazardous areas (15.8% of Italian territory) as represented in figure 1.

Thus the implementation of this large scale project would be a challenge in terms of installation and operation costs and in terms of data management.

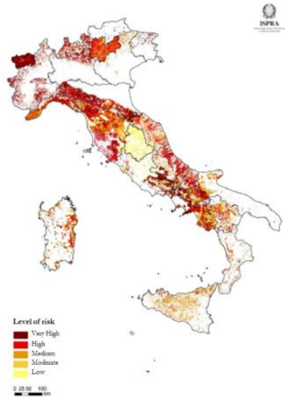

Figure 1. Level of risk due to landslide phenomenon in Italy. (ISPRA, 2015).

The use of existing lifelines systems as a part of the monitoring system is analyzed in the paper. Three reasons can be identified to promote it: the first one is a technical reason. In fact, natural gas, water distribution and other buried systems have a very high density on the territory. As reported by the last report of Eurogas (Eurogas, 2015) almost 290.000 km of natural gas pipelines are installed in Italy for an installation density of 966 m/km^2. The second reason is due to safety considerations. During soil movement buried pipelines can be exposed to high stresses and deformations with consequential failures; in this condition leakage can occur increasing the risk of a secondary hazard (Bianchini et al., 2015).

Some studies are proposed in literature to monitor pipeline status during soil movement; for example, (Li and Peng, 2016) proposes a wireless monitoring system composed of inclinometers to monitor pipelines condition during soil deformation. Also distributed optical strain monitoring systems are proposed by several authors for structure monitoring (Inaudi and Glisic, 2010; Frings, 2011). This technology consists of a continuous fiber optic cable attached to pipeline wall in which light propagates. If temperature changes or strain occurs along the path a wavelength variation (directly related to temperature and strain) occurs. It is interesting to note that, thanks to the low attenuation factor, up to forty kilometers of pipeline can be continuously monitored with an accuracy of 2μm. This system is completed by a reading unit; however, signal regeneration units can be installed if it is required to control longer lengths of pipeline.

In Table 1 the main performances of a distributed fiber optic system are reported (Inaudi and Glisic, 2010).

Characteristic	**Value**	**Measuring unit**
Measurement range	150 (Extended)	km
Spatial resolution	1 (over 5 km), 2 (over 25)	m
Temperature resolution	0.1	°C
Temperature range	-270 to +500	°C
Strain resolution	0.002	mm/m
Strain range	-1.25 to +1.25	%
Acquisition time	2	min

Table 1. Main characteristic of a distributed fiber optic system (Inaudi and Glisic, 2010).

The third reason is due to management considerations. Natural gas and water operators have more capabilities to follow and complete these types of project. Nevertheless, due to the high investment cost, economic benefits should be assured by national government. For example, for GPS systems, special algorithms are needed to achieve high spatial sensibility with cost that can reach 50.000 Euro/km^2 or higher. For fiber optic technology, instead, a broad range of cost can be defined as a function of the technology used. For long-haul Brillouin technology a cost of 1 to 2 Euro/m can be considered; also retrofit cost in existing networks should be considered in CAPEX evaluation. Furthermore, OPEX between 10% to 20% for years should be considered. Becoming part of a national preventive control system, economic incentives, as the increase of tax deductions, should be introduced to encourage operators to improve monitoring systems.

In the first part of the paper a brief description of earthquakes and earth movements characteristics is prosed. After that the interaction between soil and pipeline during ground movement is reported to characterize the phenomena and to identify variables to be controlled. In the last part of the paper possible issues and requirements for monitoring systems are analyzed.

2. Earthquake and soil movement characterization

The design of a monitoring system shall respect technical and economic issues defined during system requirements analysis and definition phase. As defined by (Intrieri et al., 2012) instrumentation has different performances as a function of the phenomenon to be monitored. Therefore, it is important to characterize natural events that are responsible of soil deformations. The most hazardous are earthquakes, which are a release of vibration energy due to the contact between moving tectonic plates in the lithosphere as firstly described by Wegener in plate tectonics theory. During the contact elastic energy is accumulated in the form of elastic strain as long as the soil stresses are lower than the yield strength of the material; exceeded this limit, plastic strain and failure of the material occurs. Accumulated energy is discharged as explained by the Rebound Theory proposed by Reid to explain damages after San Francisco Earthquake (1906). Vibrational energy reaches surface through the propagation of different types of waves, defined as primary waves (p-waves), secondary waves (s-waves) and surface waves, causing soil transient motion.

However, before an earthquake occurs local plate movements, defined as "faults", can be observed on new or preexisting offsets of the crust (Kramer, 1996). Three types of fault can be identified depending on the principal directions of the faults as reported in Figure 1 causing Permanent Ground Deformation (PGD): strike slip, normal fault and reverse fault.

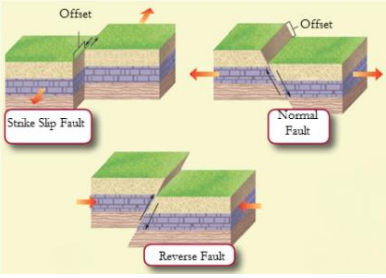

Figure 2. Type of different movement of faults causing earthquakes.

Several kinds of PGD can be induced by earthquakes or by other events defined as preparatory, triggering or sustaining depending on the type of movement induced (Terzaghi, 1952). Landslides, which are defined a movement of a mass of rock, earth and debris down a slope (Cruden, 1991), are the most hazardous for people and buildings.

Among different types, slides and lateral spreading appear to be the most frequent posing the highest risk. Slides are divided in rotational and translational: the first are "*more or less a rotational movement about an axis that is parallel to the slope contours*" (Varnes, 1978) while the second are a non-circular failure which involves translational movement. In case of slides induced by earthquakes, several correlations are proposed in the literature to evaluate PGD as a function of earthquake characteristics (O'Rourke, 2012).

Lateral spreading, instead, is the collapse of a sensitive soil layer at a certain depth followed by settlement of the above soil layer caused by the liquefaction of the below sustaining layer (Seed, 1968); it should be highlighted that this occurs only if defined soil conditions are present (Kramer, 1996).

One of the parameter to be defined during system design is the monitoring frequency. It is a main task to be identified during project requirements definition because it is responsible of control management decisions. To correctly achieve the objective, i.e. the monitoring of faults and of slides movements, it is therefore important to characterize phenomena dynamics. In the case of faults earth movements can reach velocity between 2.5 cm/year and 1.0 m/s, while the velocity class division reported in table 2 is proposed for landslide by (Cruden and Varnes, 1996).

Class	Description	Velocity, [mm/s]	Typical velocity
7	Extremely rapid	5 x 10^3	5 m/s
6	Very rapid	5 x 10	3 m/min
5	Rapid	5 x 10^{-1}	1.8 m/h
4	Moderate	5 x 10^{-3}	13 m/month
3	Slow	5 x 10^{-5}	1.6 m/year
2	Very low	5 x 10^{-7}	16 mm /year
1	Extremely slow		

Table 2. Data by (Cruden and Varnes, 1996).

Fatalities and important damages to structures have been registered for Class 6 and Class 7 events even if little data are available about occurred landslide. Therefore, monitoring system frequency should be able to record and identify at least Class 5 events.

3. Pipeline-soil interaction

The use of buried pipeline as distributed monitoring system is an application of interest to improve safety programs. However, interaction between ground deformation and pipeline must be analyzed to understand how it can be used for monitoring scope.

In literature several studies deal with the interaction between pipelines and PGD events. Ground movements are divided in longitudinal (ground movement parallel to pipe axis), transverse (ground movement perpendicular to pipe axis) and faults.

In case of longitudinal PGD (represented in Figure 3), compressive and tensile stresses arise respectively at the toe and the head of the moving slide. For longitudinal PGD strain and ground displacement can be written as (O'Rourke and Liu, 1995):

$$\varepsilon(x) = \frac{\beta_p x}{E}\left(1 + \frac{n}{1+r} \times \left(\frac{\beta_p x}{\sigma_y}\right)^r\right) \tag{1}$$

$$\delta(x) = \frac{\beta_p x^2}{E}\left(1 + \frac{2}{2+r} \times \frac{n}{1+r} \times \left(\frac{\beta_p x}{\sigma_y}\right)^r\right) \tag{2}$$

Where e(x) and d(x) are respectively pipeline strain [%] and ground displacement [m] at a distance x [m] from the head of the slide. b_p is pipe burial parameter [N/m^3], E is pipe young modulus [MPa], s_y is material yield strength [MPa] and r and n are Ramberg-Osgood material parameters.

Wrinkling phenomena that occurs at compressive side has been the first cause of failure due to longitudinal PGD (O'Rourke and Liu., 1995). This condition verifies when slide length and depth are greater than threshold values that depend on pipeline materials, type of soil and pipeline geometry (radius to thickness ratio). Figure 4 reports the couple of values for a L290 steel pipeline buried in 0.90 m of soil: the curves show that critical length and displacement are decreasing functions of the radius (R) to thickness (t) ratio. In fact, stiffer pipelines, characterized by low value of R/t ratio, are more difficult to be wrinkled.

Therefore, it can be possible to identify alarm situations by continuously monitoring slide spatial conditions.

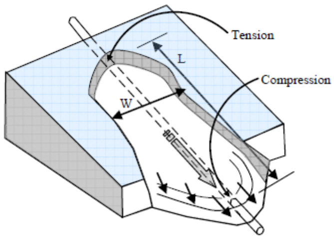

Figure 3. Schematic design of longitudinal PGD (IITK, 2007).

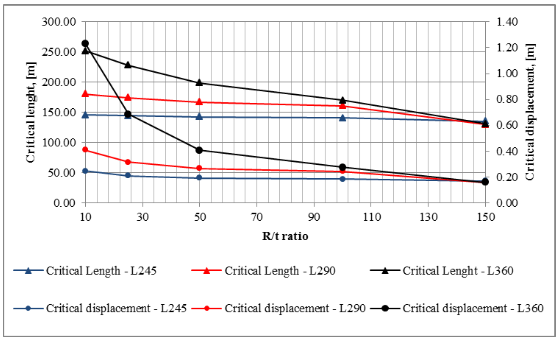

Figure 4. Critical length and displacement for different R/t ratios and L290 steel in case of longitudinal PGD.

In case of transverse PGD (Figure 5) stretching and bending conditions occur.

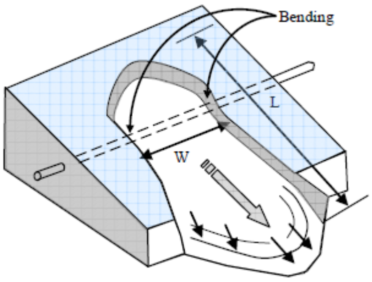

Figure 5. Schematic design of transverse PGD (IITK, 2007).

If ground deformation is spatially distributed it has been found that soil and pipeline deformations are the same until a critical ground displacement is reached (O'Rourke et al. 1997). The critical value depends on slide width and on pipeline characteristics. So, it can be calculated for each operative conditions.

A simple analytic algorithm can be implemented to identify pipeline strain from ground deformation due to the slide as reported in Equation (3):

$$\varepsilon = \begin{cases} \frac{\pi\delta}{2}\sqrt{\frac{t_u}{AEW}} \pm \frac{\pi^2\delta D}{W^2} \; if\ \delta \le \delta_{crit} \\ \frac{\pi\delta_{crit}}{2}\sqrt{\frac{t_u}{AEW}} \pm \frac{\pi^2\delta_{crit}D}{W^2} \; if\ \delta > \delta_{crit} \end{cases} \tag{3}$$

where d is ground displacement [m], t_u is longitudinal resistance [N/m], A is pipe cross sectional area [m^2], D is pipe diameter [m], W is slide width [m], E is Young modulus [Pa].

However, Equation (3) shows that it is not possible to deduce slide characteristics from strain measurement since one between slide width or displacement is defined.

Wide literature exists about pipeline performance that is subject to a soil offset. As briefly reported in Section 2 three kind of faults can be present. However, also combination of these could be observed in real cases (Figure 6).

That is, different stresses arise on pipelines. Tensile and compressive stresses are induced depending on the intersection angle between pipeline and soil direction by strike slip faults.

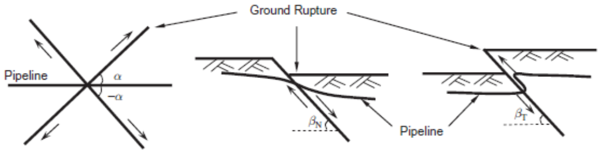

Figure 6. Different type of fault events. From the left to the right: strike slip, normal and reverse fault (Ha et al., 2010).

(Abdoun et al., 2009) describes how, in case of strike slip, different factors influence pipeline behavior discovering that axial and bending strains are increasing functions of buried depth, even if for small offset axial strain appears to be independent respect to buried depth, and to diameter. The maximum value of axial strain is found to be at the offset while bending strain present a double curvature with a zero point at the offset. By increasing the intersection angle a reduction of axial strain has been found, while bending strain remains practically unchanged. In order to increase pipeline performance against strike slip fault, remediation techniques are also performed. (Choo et al., 2007) tries to substitute soil with a more lightweight material around the pipe obtaining an improvement in case of tensile stress but a worsening in case of compressive stress. Strain due to compression presents two different peaks near to offset position which are higher respect to tensile one (Ha et al., 2010).

In case of normal and reverse faults pipeline tensile and compressive stresses arise respectively even if bending is present in both. It is noted that the induced axial strain is lower than the case of strike slip fault and that it is not symmetric with the offset path (Abdoun et al., 2008). Moreover, bending strain is a decreasing function of pipeline diameter and wall thickness but an increasing function of buried depth, offset distance and soil internal angle of friction (Naeini et al., 2016).

Only for strike slip faults analytical models are present in literature to define maximum fault offset above which safety conditions are not assured (Kennedy et al., 1977) or to calculate peak pipe strain induced in the pipeline as a function of the normalized offset, i.e. displacement to pipeline diameter ratio (Karamitros et al., 2007).

That is, pipeline safety conditions are assured until deformations are lower than the maximum allowed. In case of steel systems, it has been found that the main causes of failure are tensile and compression strain for which maximum strain are respectively 1-2% and 0.175 t/R.

The following threshold Equation (4) should be considered for the analysis of pipeline status:

$$\varepsilon_P + \varepsilon_S + \varepsilon_T \le \varepsilon_{Max} \tag{4}$$

where ε_P, ε_S and ε_T are respectively pipeline strain due to internal pressure, soil movement and temperature difference while ε_{Max} is the maximum allowed strain.

Polyethylene systems, instead, present a stress-strain relation that depends on strain rate. It has also been found that the maximum strain is an increasing function of strain rate (Merry and Bray, 1997) and correlation are proposed (Shi et al., 2014). For this material bending and cross sectional area ovalization appear to be the main cause of stress due to seismic landslide; however, it should be noted that failure is principally due to cross sectional area ovalization that induce a stress higher than yielding stress that is reported in Equation (5):

$$\sigma_y = 26.8 + 1.01 \times \ln(\dot{\varepsilon}) \qquad (5)$$

where σ_y is polyethylene yielding stress [MPa] and $\dot{\varepsilon}$ is the strain rate [s^{-1}].

Knowing this, from an installation point of view, sensors in polyethylene systems should be installed in a position A where the highest stresses are present as shown in Figure 7, where the behaviour of a 8 m pipe is reported for a strain rate of 3 x 10^{-3} s^{-1} (typical value for landslide).

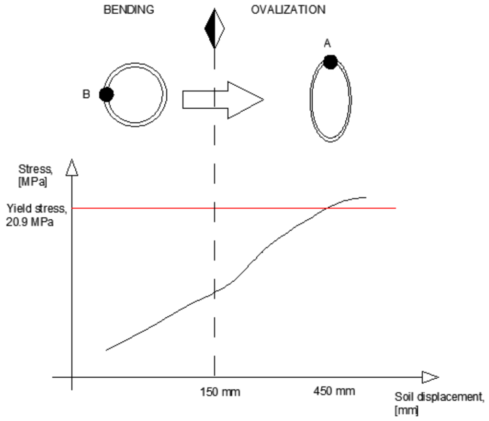

Figure 7. Stress imposed on polyethylene pipe for different soil displacement (Shi et al., 2014).

4. Soil-pipeline monitoring systems considerations

As described ground movement and pipeline strain are fully related. These two variables can be controlled in different way modifying design requirements as installation criteria. In the first case sensing devices must be installed directly on pipeline wall to recognize strain occurrence. In the second case, instead, sensors are installed above ground near to the pipeline or connected to it using, for example, existing vent tubes as bearing structures.

Some requirements and issues have to be introduced and evaluated. For the scope of the paper only a technical evaluation is proposed; in fact, several factors (size of the territory to be controlled, number of pipeline to be controlled, etc.) can radically modify the economic valuation and so it would be incorrect to define a general analysis. A technical and economic analysis will be assessed in a future work considering a real case.

The following elements are considered in the paper: implementation, operation, maintenance, requirements due to working environments, required number of sensors.

1. Implementation. In the case of sensing devices installed directly on pipe structure several issues can arise in the retrofit of existing networks. In (Bianchini et al., 2016) it has been estimated that installation is the highest voice of cost and so buried monitoring should be selected only for new pipelines or in case of replacement of an existing one in accordance to maintenance programs.
   Instead, unburied monitoring devices are easier to be installed in case support structures near to pipeline are present. Furthermore, respect to buried ones, for which great attention and specialized workers are required during installation phase to avoid damages to sensors, unburied solutions can be installed easily and rapidly without the need of expert teams.
2. Operations. Monitoring systems shall be electrical supplied. Photovoltaic sources with dedicated backup batteries can be installed to ensure the entire consumption. It is however possible to have devices powered only by batteries. In this case attention must be given also to define correctly the sampling rate since battery capacity depend on chemistry used, environment and load conditions (data elaboration and transmission). Considering the dynamic of the phenomenon under monitoring, it should be possible to implement different data analysis frequency as a function of the velocity class proposed in table 2. Moreover, data transmission should be maintained at the minimum to reduce power consumption: so, a preliminary data analysis should be performed by a local unit and transmitted to the central unit once a day or when thresholds are exceeded.
3. Maintenance. Design phase should consider all the activities to be performed when a device fails. Repair activities appear to be more critical for buried devices than for unburied ones because of the lack of accessibility. In addition, it should be considered that in case of pipeline failure and consequent replacement, monitoring systems should be affected the least possible. Respect to buried devices, unburied ones appears to be more insensitive to this point, ensuring less management issues.
4. Requirements due to working environment. Specific requirements must be defined for both the devices. First of all, Ingress Protection (IP) shall be identified in accordance to CEI EN 60529/1997 to ensure the entire design life in different working conditions. In addition to dust and water possible presence, the occurrence of flammable or explosive atmosphere must be considered. The installation of electrical devices on NG networks or near to them requires the analysis about the presence of hazardous zones in accordance to CEI EN 60079-10 defining the necessity to use devices compliant to Atmosphere Explosives (ATEX) Directive. In fact, during operations several type of accidents can cause natural gas leakage that can ignite in case of the mixing with air and of the presence of an ignition source.
5. Required number of sensors. Different considerations arise if strain or ground monitoring is

selected. In the first case, literature demonstrates that strain conditions in a defined point of the pipeline are directly related to the ground movement in that point. In particular, in case of faults, total strain appears only near to fault offset. Therefore, buried monitoring systems should be able to control continuously strain conditions. Instead, unburied system can be able to identify ground movement also if they are installed far away from the fault; however, the number of sensors depends on the size of the landslide or of the territory to be controlled. No method to identify the correct number of sensors as a function of ground displacement and area size can be found in literature: so, this is a research area that needs further improvements.

As described before unburied systems present several advantages respect to buried systems. On the other hand, it should be considered the following:

1. Authorization. To ensure ground movement characterization several devices must be installed in a large area; in urban area authorizations have to be required if installation is completed in private properties.
2. Vandalism. Unburied devices could be subject to damages by third parties causing economic losses and false alarms.
3. Possibility to monitor other phenomena. The installation of strain sensors through pipelines could ensure the monitoring of other events like fluid leakages from holes caused by overstressed load conditions. In fact, pressure waves are produced during leakage conditions and they propagate in the pipeline producing strains on the wall.

In accordance to the requirements identified two different technologies are considered manageable for the scope: Global Positioning Systems (GPS) and distributed fiber optic strain systems. The first one could be installed attached to NG vent structures in accordance to an ATEX assessment as proposed in Figure 7 (circled in red) while distributed fiber optic cable could be installed along pipe springlines to measure total and axial strains; furthermore, the use of light is free from ATEX assessment.

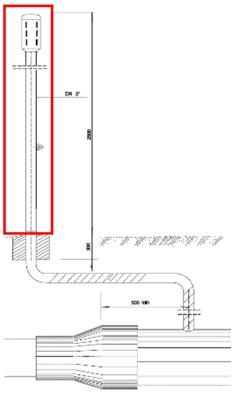

Figure 7. Proposed position for GPS device in accordance to SNAM.

5. Conclusion

The possibility of monitoring simultaneously ground movement and buried pipelines status can ensure great improvements in the actuation of safety preventive plans and ensure enhancements for mitigation operations after events. Ground movement or pipeline induced strain can be monitored to read the evolution of environment conditions. Correlations between deformation and strain can be defined as a function of the kind of ground movement. Monitoring activities could be performed by lifelines operators but economic benefits (i.e. incentives, tax reduction/deduction) should be ensured by national government to promote and sustain part of the economic investment as a reward for the realization of higher safety performances against ground movement hazards.

However, several requirements shall be respected during the design phase; in a first analysis unburied systems seems to be easily implemented than buried ones, even if environment constraints, as physical obstacles or other issues as authorization and vandalism could reduce their performance. A case by case techno-economic analysis has to be performed to identify the best monitoring system to be implemented. A detailed analysis considering real cases will be proposed in a future work to evaluate the effective implementation of the proposed technologies or other ones from a technical and economic point of view.

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