

Probabilistic Risk Assessment of Buried Steel Natural Gas Pipelines Exposed to Axial Landslide Deformations Induced by Rainfall Infiltration – The Miscano landslide

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1 INTRODUCTION & SCOPE OF WORK

Due to the extensive spatial distribution of natural gas pipeline networks, their buried components often traverse diverse topographies, including sloping terrains. Such slopes may be susceptible to landslides triggered by various factors, such as intense rainfall, seismic events, and human activities. These ground movements can adversely affect buried natural gas pipelines, potentially causing damage and, in severe cases, structural failure with all the potential consequences. As an example, on July 31, 2014, a series of explosions from an embedded gas pipeline occurred in Kaohsiung, Taiwan, resulting in 32 deaths and 321 injuries (Yang et al., 2016).

Developing an appropriate risk assessment framework may contribute towards risk-informed pipeline integrity management, enhancing the resilience of buried natural gas pipelines.

In this context, this research develops a probabilistic risk assessment framework of buried steel natural gas pipelines exposed to axial landslide deformations induced by rainfall infiltration considering the case study of Miscano landslide in Italy.

2 METHODOLOGY

The developed risk assessment framework consists of three main steps, i.e., the hazard assessment step, the vulnerability assessment step, and the consequences assessment step. For the hazard assessment, the framework derives hazard curves based on the predictions of a well calibrated and validated numerical model of Miscano landslide. The numerical model employs a Mohr-Coulomb constitutive model for the simulation of the ground response under intense rainfall ground deformations (Tawalo et al., 2025a). The analysis is carried out by changing the hydro-mechanical parameters of the examined slope (φ', c', k) based on their probability distributions and then performing statistical analysis in terms of multi-linear regression in order to develop ground displacement prediction equations. The resulting hazard curves correlate the yearly cumulative ground displacements with the probability of non-exceedance in one year.

The vulnerability assessment is carried out through the development of analytical fragility functions, derived from statistical analysis of numerical data obtained from a parametric study conducted using a 3D soil-pipeline interaction numerical model after adopting linear elastic-perfectly plastic model for the pipeline and linear elastic for the ground material. This model simulates local buckling as the governing structural instability, assuming that the pipeline is aligned with the direction of landslide movement. The resulting fragility functions relate

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differential permanent ground displacements to the probability of exceeding a specified limit state, which is defined herein by the onset of local buckling instability.

For the potential consequences of a buried natural gas pipeline failure, the proposed framework adopts an Event Tree Analysis (ETA) approach based on methodologies developed in the literature specifically for buried natural gas pipelines (Vairo et al., 2021). The adopted ETA is applied probabilistically to systematically assess the range of possible outcomes following a buried steel natural gas pipeline failure event. This ETA includes explosion, jet fire, flash fire, and gas dispersion, incorporating uncertainty and conditional branching to quantify the likelihood of each consequence scenario.

3 RESEARCH OUTCOMES

Figure 1 illustrates the developed risk assessment framework for buried steel natural gas pipelines exposed to axial landslide displacements induced by rainfall, considering the Miscano landslide as a case study. The figure incorporates the geotechnical profile implemented in the finite element code PLAXIS 2D to numerically simulate slope-atmosphere interaction for the Miscano slope (Figure 1a), as well as a three-dimensional soil-pipeline interaction numerical model developed using PLAXIS 3D to derive analytical fragility functions for the affected pipelines (Figure 1b).

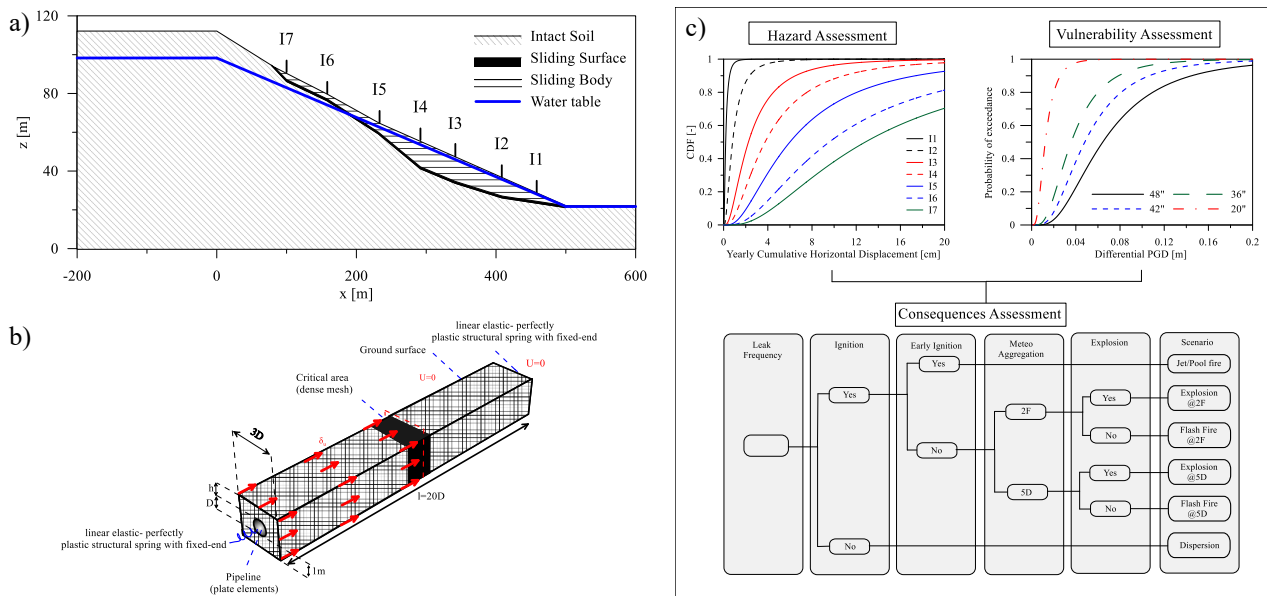


Figure 1. a) Geotechnical profile of Miscano landslide, b) numerical model for the soil-pipeline interaction analysis, c) proposed risk assessment framework.

For the hazard assessment, the derived from the first step, hazard curves represent the predicted landslide deformations at different locations along the slope (Figure 1a). These curves indicate that, for the same probability of non-exceedance, the yearly cumulative horizontal displacement increases when moving toward the base of the slope. This trend is mainly attributed to the increase in groundwater table depth, which allows for larger groundwater fluctuations and, consequently, greater pore water pressure development at the depth of the sliding surface. The resulting reduction in shear strength ultimately leads to larger horizontal displacements.

Fragility functions, derived for pipelines with different diameters, reveal that an increase in pipeline diameter leads to reduced vulnerability to axial landslide-induced deformations, compared to smaller pipelines. This behavior is attributed to the increase in cross-sectional area associated with larger diameters, which enhances the axial stiffness of the pipeline, allowing it to resist higher levels of axial compression and to accommodate greater axial ground deformations before the onset of local buckling instability.

For the consequence assessment, it is found that a flash fire resulting from delayed local ignition is the most probable consequence scenario following the failure of buried steel natural gas pipelines under the examined loading conditions (Tawalo et al., 2025b).

REFERENCES

- Tawalo, A., Falcone, G., Pirone, M., d'Onofrio, A., & Urciuoli, G. (2025a). Numerical modelling of displacements induced by rainfall infiltration in a clayey soil slope: The Miscano (Southern Italy) case study. *Computers and Geotechnics*, 184, 107267.
- Tawalo, A., Tsiniadis, G., & Urciuoli, G. (2025b). Numerical framework for risk assessment of buried natural gas pipelines subjected to landslide-induced deformations due to rainfall infiltration: The Miscano landslide case. *International Journal of Disaster Risk Reduction*, 129, 105776.
- Vairo, T., Pontiggia, M., & Fabiano, B. (2021). Critical aspects of natural gas pipelines risk assessments. A case-study application on buried layout. *Process Safety and Environmental Protection*, 149, 258–268.
- Yang, H.-N., Chen, J.-H., Chiu, H.-J., Kao, T.-J., Tsai, H.-Y., & Chen, J.-R. (2016). Confined vapor explosion in Kaohsiung City – A detailed analysis of the tragedy in the harbor city. *Journal of Loss Prevention in the Process Industries*, 41, 107–120.