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A performance-based NaTech risk assessment methodology for hydrocarbon pipelines subjected to landslides

Fabrizio Paolacci [a,*], Daniele Corritore [b], Stefano Caprinozzi [b], Iacopo Borsi [c], Maria Giulia Sotgiu [c], Michele Bonuccelli [c], Marcello Mancini [d], Vito Tonetto [d]

[a] *Department of Civil, Computer Science and Aeronautical Technologies Engineering, Roma Tre University, Via Vito Volterra 62, 00146, Rome, Italy*
[b] *Safeplant SrL, Via Magna Grecia 30/A, 00183, Rome, Italy*
[c] *TEA Sistemi SpA, Via Ponte a Piglieri, 8, 56122, Pisa, Italy*
[d] *ENI SpA, Piazzale Enrico Mattei 1, 00144, Rome, Italy*

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ABSTRACT

Distributed gas and oil pipelines often cross areas prone to landslides. According to the Eu Directive 2012/18/UE, known also as Seveso III, the risk to people and community served by the pipeline should be assessed. If the need is clear, the state of the art on available methods to solve this peculiar problem is limited. Methods to calculate NaTech risk according to a performance-based approach have already been proposed, especially for hazardous plants like refineries and oil & gas plant. Differently, a few similar approaches have been used for estimating the risk of consequences generated by a hydrocarbon material release from a pipeline subjected to landslide. In this paper a performance-based methodology to assess the mean annual frequency of release from pipelines for the transportation of hydrocarbons subjected to a landslide is proposed. This methodology employs the hazard curves of landslides, and the fragility curves of the pipelines defined in terms of permanent ground deformation. The content release is evaluated by using mechanical response quantities as local deformation as suggested in the literature. The proposed approach is validated through a representative case study of a pipeline for the transportation of oil crossing in a mountain region.

1. Introduction

1.1. Background and motivation

In the recent past, it has been well documented how natural events can cause a series of consequences (fires, explosions, toxic or radioactive fumes, spills of pollutants, etc.) to installations or infrastructures that process, store or transport hazardous materials, including hydrocarbon fluids through shallow and buried pipelines [1]. These accidents caused by natural events are called NaTech (Natural Hazards triggering Technological Disasters). An analysis of the information provided by the most important databases on industrial accidents (e.g. MARS of the European Commission, MHIDAS in Great Britain, ARIA in France) demonstrates that about 3%–4% of accidental events occurring at industrial sites are caused by the impact of natural events. Among these, those

* Corresponding author.
E-mail addresses: fabrizio.paolacci@uniroma3.it (F. Paolacci), daniele.corritore@safeplant.it (D. Corritore), stefano.caprinozzi@safeplant.it (S. Caprinozzi), iacopo.borsi@tea-group.com (I. Borsi), mariagiulia.sotgiu@tea-group.com (M.G. Sotgiu), michele.bonuccelli@tea-group.com (M. Bonuccelli), marcello.mancini@eni.com (M. Mancini), vito.tonetto@eni.com (V. Tonetto).

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events linked to climate change, whether hydrological/hydrogeological (floods, landslides) or meteorological (flooding due to heavy rain, lightning, high winds and tornadoes) have gained increasing importance in recent years [2]. Geohazards represents one of the main causes of buried pipelines rupture and the potential development of NaTech events, because of the large displacements generating from different possible events as slope failure, earthquake triggered slope movement, surface faulting and subsidence, lateral spreading, creep, [3–5]. Differently from transient ground deformation, permanent ground displacements (PGD) induced by landslides, represent a very critical effect for buried pipelines, mainly because of the large extension of the pipeline routes and thus their unavoidable interaction with unstable slopes,[6–9]. In Europe, pipelines NaTech accidents represent 4% of all reported oil and petroleum product pipeline accidents over the past 40 years, from 1971 to 2012, [10,11]. Landslides and subsidence were responsible for 65% of the pipeline NaTech accidents in Europe, 20% were related to floods, and 10% were triggered by climate change effects. The estimated cost of these accidents is about 40ML million Euro, [11]. In USA the Geological hazards (mainly subsidence, frost heave and landslides) caused a high percentage of pipeline NaTech accidents (27%) with 10% of the total cost, [12].

Thus, it is clear that the effects of unfavorable ground conditions on buried pipelines need attention. Therefore, the use of proper tools for the assessment of NaTech risk represents a clear need. Unfortunately, few contributions are currently available in the literature. Different approaches could be adopted in NaTech risk assessment of pipelines subjected to landslides, depending on the scope of the analysis, but a modern approach such as the performance-based assessment (PBA) approach is recommended, which combines hazard and pipeline vulnerability information for the quantification of the risk. The performance-based approach has been mainly developed in earthquake engineering [13] but has been rapidly adopted in different areas of civil engineering [14]. In the industrial field the application of the PBA is still lacking even though in NaTech Risk assessment a countertrend is evident [15–23]. Nevertheless, applications of PBA to pipelines exposed to natural hazards are rather limited and often confined to the seismic field and seismic-related geohazard conditions. A rapid risk assessment methodology of NaTech risk for pipelines has been proposed in [24]. This methodology implemented in the Rapid-N tools is a scenario-based approach that adopting user-defined on-site-hazard information, literature fragility curves [25] and user-defined or automatically calculated incident points, evaluate the impact zones. RAPID-N has currently been implemented to assess and map earthquake impacts on specific hazardous facilities as process, storage facilities, and oil pipelines. However, geohazard conditions are not currently available. Amaducci et al. (2024) proposed a novel procedure to assess the NaTech risk and consequences due to earthquake including local specific individual risk and societal risk due to NaTech events along the route of pipelines, [26]. This approach can be profitably used for the evaluation of the risk of a pipeline and to individuate the critical sections of the route, based on which a more refined risk analysis (local) should be performed. De Risi et al. (2018) proposed a Scenario-Based Seismic Risk Assessment for Buried Transmission Gas Pipelines at Regional Scale, [27]. In this work seismic geohazard-induced were considered and more in particular cascading landslide and liquefaction hazards, providing a hybrid empirical-mechanical-based estimation of permanent ground displacements (PGD) and damage maps, as decision-support tools for network managers and stakeholders. Dey and Tesfamariam (2022) proposed a novel method to estimate regional seismic risk to buried continuous pipelines that includes many uncertainties (earthquake rupture, soil properties at the site, geometric properties of pipes, operating conditions), [28]. They used a stochastic earthquake source modeling and analytical solutions to generate regional ground deformation and a multi-fidelity Gaussian process surrogate model to predict failure probabilities at different levels of permanent ground deformation to compute the fragility curves and ensure computational efficiency. From the above considerations emerges a clear gap in using the PBA in the context of NaTech risk assessment of pipelines subjected to geohazard conditions and more in particular to landslides. An additional effort to fill the gap could help the operators in the energy sector dealing with effective emergency plans against such a natural events.

1.2. Scope

In summary, to formulate an integrated PBA framework both for shallow and buried pipelines subjected to landslides, the following objectives are pursued hereinafter: (1) definition of landslides hazard assessment methodologies and selection of suitable intensity measures for the quantification of mean annual frequency of occurrence, also in seismic conditions; (2) formulation of a PBA methodology to derive fragility curves in a specific section of the pipeline by using Winkler and FE models; (3) NaTech risk assessment in terms of mean annual frequency (MAF) of occurrence of specific damage conditions generating release phenomena (LOC) in pipelines. An illustrative example of buried pipeline for oil transportation is used to validate the proposed PBA framework. The selected pipeline section is located in a mountain region with a significant and different number of landslides phenomena, but with more frequent rotational/translational slides. The paper is organized as follows. Firstly, in Section 2 the performance-based NaTech risk assessment methodology is formulated, including, (i) a deep investigation on landslide hazard assessment methodology and the definition of proper intensity measure, (ii) formulation of a methodology for deriving fragility curves of pipelines subjected to landslides phenomena, (iii) derivation of MAF of pipelines in presence of LOC events. Section 3 presents the NaTech risk assessment of an illustrative example of buried pipelines. Section 4 is devoted to the discussion of the results. Finally, Section 5 draws conclusions and future perspectives.

2. A performance-based NaTech risk assessment methodology

2.1. Formulation of the methodology

In this section a Performance-Based Risk Assessment methodology for buried pipelines is proposed. The breakdown of the methodology is illustrated in Fig. 1 where the several phases of the methodology are shown and in particular:

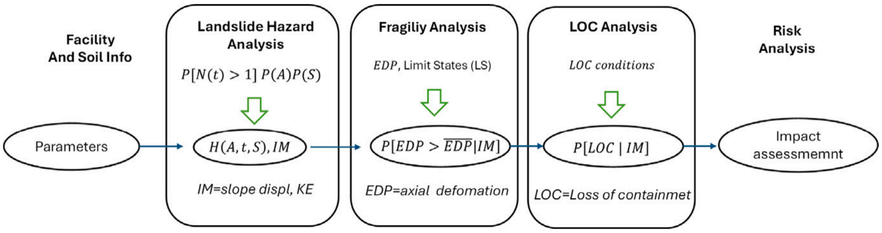


Fig. 1. LOC risk assessment method.

- Identification of input parameters
- Landslide Hazard Analysis
- Fragility Analysis of pipeline
- Loss of containment and risk analysis (LOC)

The proposed method is based, as illustrated in the following paragraphs, on the synergic use of hazard and vulnerability information. Concerning the former, it is necessary to gather susceptibility and the landslide index maps. It is also necessary to get landslide data in order to calibrate the coefficients of the landslide frequency curve for a given magnitude (area or volume). With the available statistical data of the landslide, it is theoretically possible to build local susceptibility maps, in terms of probability of occurrence of a landslide in a zone S, $P(S)$, and with a given area A, $P(A)$, as well as the probability of occurrence of at least one landslide event in a given time period t, P[N(t) > 1]. The vulnerability to landslides of pipelines is mainly related to the selection of proper engineering demand parameters (EDP) and limit states (LS). EDP is usually identified with the maximum axial stress, whereas the definition of LS is still an unsolved problem, especially for the identification of a clear relationship between Damage and LOC. With the idea to formulate a Performance-based methodology, using which the mean annual frequency of exceeding a certain landslide intensity measure (IM) is calculated and the fragility curve for damage states associated to LOC conditions in terms of axial deformation ε_{LOC}, is built, as explained afterwards; the risk expressed as mean annual frequency of occurrence of a LOC event, is given by:

$$P(LOC|IM) = \int_{-\infty}^{\infty} P(\varepsilon > \varepsilon_{LOC}|IM) d\lambda(IM) \tag{1}$$

In the following paragraphs, methods for hazard and vulnerability analysis will be discussed, and the methodology for the risk assessment, according to Eq. (1) will be formulated.

2.1.1. Methods for landslide hazard assessment

Landslide hazard analysis can be performed using different approaches, summarized in Table 1, where qualitative and quantitative methods are indicated. Qualitative methods, which are based on the geomorphological analysis of the terrain, the aerophotogeological interpretation of the area and the census of already known phenomena, are not useful for the quantification of landslide hazard and only serve to identify the areas of greater susceptibility on which to conduct analyses of a quantitative nature. Quantitative methods, on the other hand, are dedicated to the realization of hazard maps. The latter is defined as the probability H of a landslide phenomenon in a given area, in a given time interval and with a given extension:

$$H(A,t,S) = P(A) \cdot P(N(t) > 1) \cdot P(S) \tag{2}$$

where A is the area subjected to landslide phenomenon and S is its extent. The $P(A)$, referred in the following as "landslide index", is the probability that the area of the landslide is larger than A, usually expressed as the ratio of the landslide area to the total area of the site of interest. It may be expressed at the municipal, provincial, regional or entire national level [29]. Finally, $P(N(t))$ is the probability of occurrence of at least one landslide event in a given time period t, and $P(S)$ is the probability that the landslide phenomenon will occur in area S, also known as susceptibility. The method here adopted incorporates the randomness associated with all three components of the hazard. This means that a better capacity of the model to get reliable results will depend on the reliability of the single components. Nevertheless, the proposed methodology formulated in Section 2.1 is transparent with respect to this problem. The lower the dispersion in the hazard the higher the accuracy in the risk quantification, even though the structure of the methodology remains intact.

Landslide susceptibility is commonly expressed as the probability of spatial occurrence of a landslide, given a set of spatial and environmental data, [30]. It is a measure of the degree to which an area is likely to be affected by landslides, i.e. an estimate of 'where' landslides are likely to occur. Susceptibility does not consider the temporal recurrence, nor the size of landslides. Different methods have been proposed in past for producing susceptibility maps [31]. Landslide susceptibility maps are preparatory to landslide hazard and risk zoning. For example, in Europe the landslide susceptibility map ELSUS 1000 released through the European Soil Data Centre has been published in 2013 [32], and recently updated [33]. Susceptibility maps for the whole Italy territory are also available (https://idrogeo.isprambiente.it/app/iffi/f/0067129600), [34]. In this mapping system, five susceptibility levels are

Table 1
Different methods for landslides hazard analysis.

Components	Short-cut	Standard	Best Estimate
Susceptibility	Landslides Inventory	Deterministic Methods: *Slope Stability Analysis* Statistic Methods: *Landslides susceptibility maps*	Statistical Methods: *Processing Models of Monitoring Data for Landslide Probability Estimation*
Landslide Inventory	–	Analytical Methods	Static Methods: *Static processing models of monitoring data for estimating annual landslide probability*
Mean annual frequency of the landslides	–	Analytical Methods	Static Methods: *Static processing models of monitoring data for estimating annual landslide probability*
Landslide Intensity (displacement or kinetic energy)	–	Analytical Methods: *Rigid block sliding methods rockfall methods*	Analytical Methods: *Finite Element Methods Ad Hoc Methods*

considered, from AA (attention class) to P4 (very high susceptibility), with increasing severity. The corresponding probability are respectively $< 25\%$ for P4, between 25% and 45% for P3, between 45% and 55% for P2, between 55% and 80% for P1 and $> 80\%$ for AA. The database contains also data on all known landslides in the Italian territory, as well as the presence of monitoring systems.

The derivation of P(A), starts from a distribution of landslide areas, which is typically obtained from digital landslide inventory maps. Consequently, the frequency distributions of landslide areas can be obtained; noncumulative frequency–area distribution correlates well with a power-law relation, [35].

The probability $P(N(t) > 1)$ of occurrence of a landslide in a given period of time t can be quantified with Poisson or binomial models [36]. These probabilities are generally estimated on the basis of historical landslide data from the area of interest. If a Poisson distribution is adopted, it would be expressed as follows:

$$P(N(t) > 1) = e^{\lambda \cdot t} \tag{3}$$

where $\lambda = P[N = 1|t = 1]$ is the average annual frequency of occurrence of a landslide with a given intensity (displacement, volume or kinetic energy), the inverse of which is the return period of the landslide $T = 1/\lambda$. The mean annual frequency of occurrence of a landslide can be determined on the basis of in situ measurements of landslide phenomena and, in addition, satellite information. Alternatively, it is possible to determine the probability of exceeding a certain landslide intensity (displacement or volume) through numerical approaches by generating, for example, through Monte Carlo analysis a series of landslide conditions by varying, given the landslide surface, the most significant geotechnical parameters, although the variabilities involved are so high that it is difficult to generate reliable samples, [37]. An example of susceptibility and landslide index is shown in Fig. 3(b).

With the identification of the areas with the highest susceptibility and in which there are pipelines of the oil/gas pipeline, and thus known the probability of the landslide occurring, one can then proceed with the estimation of the selected landslide intensity. The latter, in the case of deep or shallow landslides, is usually represented by the displacement of the land mass or even its volume. In this case, it is possible to estimate the displacements downstream of the landslide using methods of a different nature, depending on whether the landslide is deep (translational and/or rotational landslides) or superficial (rock mass fall, debris flow), [38]. The case of very slow superficial landslides is different, which generally involve viscosity phenomena of the soil layers that, as known, are difficult to assess and must necessarily be monitored [39,40]. Very slow slips are also more easily controlled with countermeasures that can be put in place before there is an irreversible damage to the pipes.

In the case of deep landslides, the most suitable measure of landslide intensity is the displacement that the earth mass imposes on the pipe, the estimation of which can be carried out by numerical methods, with deformation analysis of the landslide volume moving rapidly along the sliding line [3], or by simplified methods that estimate the motion of the landslide block by assuming the conservation of its volume during motion [41]. The case of superficial landslides, such as rockfall, can be an equally dangerous event in the presence of both surface and deep pipes [42]. In this case, the most suitable intensity parameter is the kinetic energy, which is a parameter related to the impact force that a rock can apply to the pipe or to the soil that covers it, and thus to the potential damage on the pipe [36].

The case of landslides generated by a seismic event and its effects on pipes is different. De Risi et al. (2018), [27] proposed an expeditious method for buried pipes that includes different steps:

- assessment of the landslide susceptibility
- evaluation of the triggering conditions of the landslide as a function of seismic acceleration
- calculation of the peak displacement PGD (Permanent Ground Displacement)

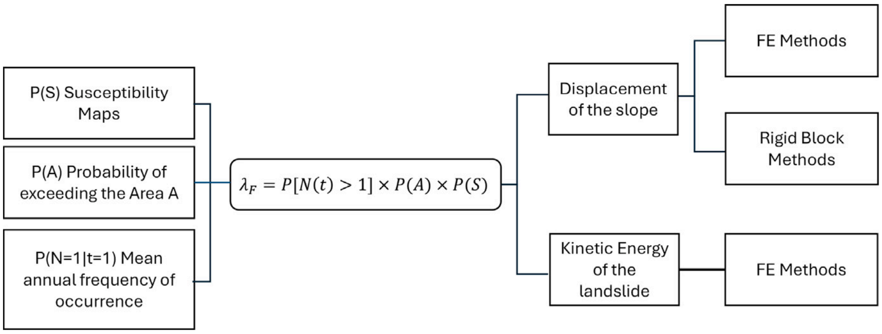
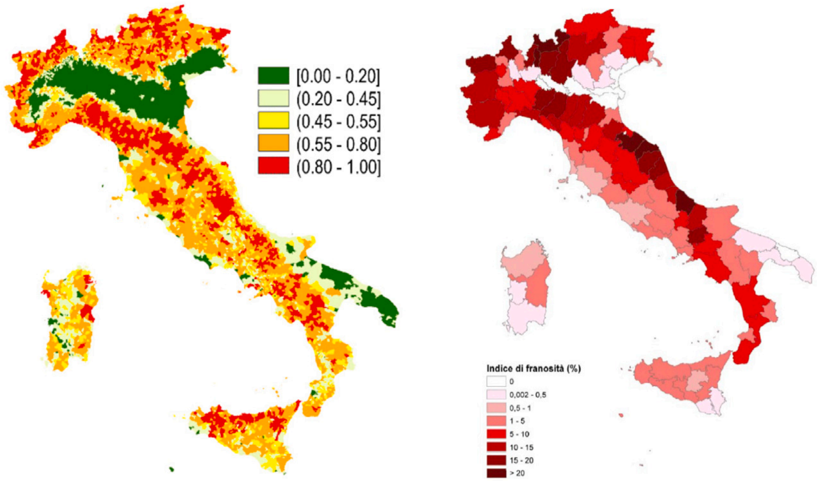


Fig. 2. Landslide hazard assessment method.



(a) (b)

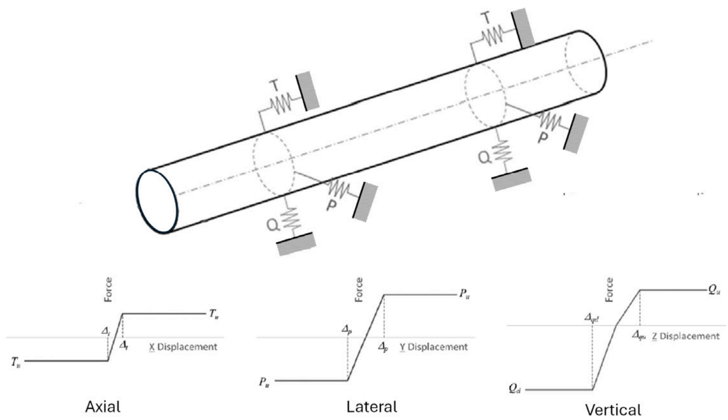
Fig. 3. (a) Susceptibility map (b) Landslide index maps [34].

Susceptibility is essentially related to the magnitude of the earthquake and the type of landslide, [43]. Safety domains are available as a function of distance from the epicenter and magnitude, using which potential landslide conditions are assessed. If the type of landslide is not known, the most conservative condition is taken. Landslide triggering conditions can be evaluated by adopting the Newmark model, [44], which allows the safety coefficient to be estimated, on the basis of which the critical acceleration capable of triggering the landslide will be evaluated. With the triggering condition of the landslide it is possible to determine the peak landslide displacement PGD on the basis of empirical relationships. Saygili and Rathje (2009), [39] suggested an empirical relationship of the PGD as a function of the peak acceleration PGA and the peak velocity PGV. In case of seismic wave propagation, the Transient Ground Displacement (TGD) would be more appropriate, as investigated in [6] and more recently in [45,46]. However, this case has not been analyzed and will be the object of future research.

Landslides scenario conditions are generally used to assess the risky conditions of a pipeline. Consequently, it is possible to proceed with the selection of a seismic attenuation law, based on which one can generate PGA and PGV samples using the Monte Carlo method under the hypothesis of lognormal distribution. Thus, is possible to build the PGD statistics (mean and standard deviation). In particular, a disaggregation analysis can be performed to identify the most probable magnitude and distance. The general framework for the quantitative landslide hazard analysis previously detailed is illustrated in Fig. 2.

Anyhow, to conduct hazard and vulnerability analysis of a pipeline in a landslide area, a minimum number of parameters is required, as listed below:

- Geological and geomorphological map
- Digital terrain models (DTM)
- Susceptibility map and landslide index
- Data on past landslides
- Landslide geometry
- Geotechnical data of the landslide terrain



$$T_u = \pi D H_p \gamma \frac{1+K_o}{2} \tan(\delta) \qquad P_u = N_{ch} c D + N_{qh} \gamma H_p D \qquad Q_d = c N_c D + \gamma H_p N_q D + \frac{1}{2}\gamma D^2 N_\gamma$$

$$Q_d = N_c\, c\, D + N_q\, \gamma\, H\, D + N_\gamma \gamma\, \frac{D^2}{2}$$

Fig. 4. Winkler model of a buried pipeline [50].

2.1.2. Fragility curves for pipelines subjected to landslides phenomena

In case of deep and shallow landslides, a pipe could be subjected to a lateral pressure due to the ground sliding. On the contrary, collapse/tilting of rock masses could generate critical impact phenomena. In what follow, only the case of deep and shallow landslides will be analyzed leaving to the future analyses the phenomenon of rock falls.

Since neither catalogue of fragility curves for such a condition nor empirical approaches are available in the literature, to the best knowledge of the authors of the present paper, numerical approaches can be used for to build fragility curves. In this respect, low or high-fidelity models can be employed, as for instance [47,48].

A simple and effective modeling approach is to adopt beam models subject to a lateral pressure generated by the landslide front. The pattern of the pressure front depends not only on the width of the excavation face w, but also on the type of soil and the maximum displacement generated by the landslide (PGD=δ). This distribution can generally be considered of sinusoidal type, [9].

For a correct simulation, both the landslide front and the remain parts must be appropriately modeled, including the interaction with the structure. A classical approach is based on Winkler models where the soil is modeled with appropriate non-linear springs [9]. Fig. 4 shows a model of an underground pipeline including winkler soil–structure interaction, where D represents the diameter of the pipe, α the adhesion factor, c the cohesion of the surface layer, H the depth of the pipe, γ the weight per unit volume of the surface layer, K_0 represents the at-rest pressure earth coefficient set equal to 1, while δ represents the angle of friction between the soil and the pipe. N_{ch} and N_{qh} represent the horizontal capacity factors of clays and sands respectively, evaluated in accordance with the ALA guidelines [49]. For the vertical springs, the behavior differs for compression and tension components. In equations of Fig. 4 the vertical bearing capacity factors N_{cv}, N_{qv} and the transversal ones N_c, N_q and N_γ are determined according to [49], as a function of the soil friction angle ϕ. The pipe can be modeled with elastic or elastic–plastic beam elements. Such a model can easily be used for the generation of fragility curves by determining the maximum displacement δ as the landslide intensity parameter. This is fully consistent with the hazard analysis for which the maximum displacement of the landslide front is typically chosen, as discussed in section 2.1.1, as intensity parameter.

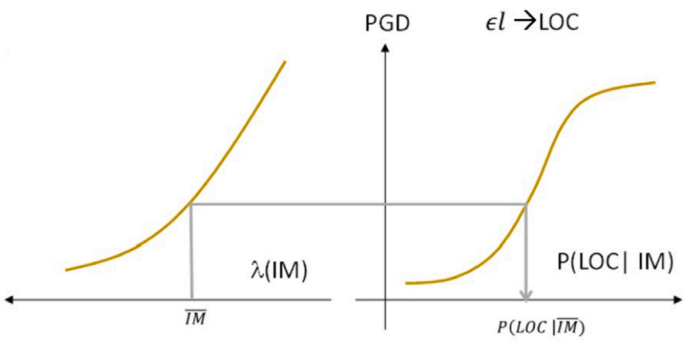
By varying the various parameters governing the problem (geotechnical parameters, pipe depth H, maximum displacement δ), it is possible to generate a series of samples of the response parameters representing the limit state. Those capable of generating material releases are chosen as limit states, as shown in Table 2. In this case, the response parameter is represented by the local deformation of the pipe. Consequently, the fragility curve can be constructed by means of a lognormal regression. Alternatives to numerical models are represented by analytical solutions, even though they are not always easy to use, such as the one proposed by Chaudhuri and Choudhury (2020), [51].

High-fidelity models are represented by finite element models to model both for pipe and the surrounding terrain. Such models, however, are not typically used for fragility analyses due to the computational burden, which is usually high. In this case, surrogate models can be used, [52].

2.1.3. Loss of containment events (LOC) and risk analysis

Given the hazard curve, or mean annual frequency of occurrence of the reference landslide scenario and the fragility curves, it is possible to combine them, using the total probability theorem, as synthetically shown in Fig. 5, where the mathematical meaning of Eq. (1) is shown. Because landslide scenarios could be of a certain interest, the expression of the mean annual frequency of occurrence of a given scenario $\lambda(LOC)_S$ can also be provided.

Selected the limit states associated with the LOC conditions, it is possible to calculate the mean annual frequency of occurrence λ of the LOC by integrating the fragility curve associated with the LOC condition over all values of the IM intensity. However,



$$\lambda(LOC) = \int_{-\infty}^{+\infty} P(\epsilon > \epsilon_{lim}|IM)\, d\lambda(IM) \qquad \text{Risk}$$

$$\lambda(LOC) = P(\epsilon > \epsilon_{lim}|\overline{IM})\, \lambda(\overline{IM}) \qquad \text{Scenario}$$

Fig. 5. Procedure for calculating the mean annual frequency of occurrence of the LOC.

Table 2
Limit States and LOC conditions, [53].

Limit state	Maximum limit axial compressive strain	Description	ε_c defined following
Operable Limit State (OLS)	$\varepsilon = \min(0.01, 0.4 \times t/D)$	Despite some minor plastic deformations, the pipeline will operate immediately after the event.	[49]; [54]; [55]
Pressure Integrity Limit State (PILS)	$\varepsilon = \min(0.04, 1.76 \times t/D)$	Despite some significant deformations on the pipe, no leakage of containment is taken place.	[49]; [54]; [56]; [57]; [58]
Ultimate Limit State (ULS)	$\varepsilon = \min(0.1, 4.4 \times t/D)$	A ‘controllable’ release of the containment of the pipeline is expected.	[59]; [57]; [58]
Global Collapse Limit State (GCLS)	$\varepsilon = 0.15$	A structural collapse is reported.	[60]; [61]; [62]; [58]

the limit states capable to generate LOC conditions have not been extensively studied in the literature. An interesting proposal has been formulated by Jahangiri and Shakib (2018) [53]. They performed a seismic evaluation of buried pipelines subjected to earthquake-induced transient ground motions, deriving a useful indication to link limit states and loss of containment events as shown in Table 2, in which the several references are also reported. This represents one of a few systematic examples of limit state-LOC relationship that can be profitably used in the risk analysis of pipelines subjected to landslides.

If we were interested in single scenarios, it would be enough to multiply the fragility curve corresponding to a given hazard intensity (IM) by the corresponding mean annual frequency of occurrence of the intensity measure IM.

When a release from a pipeline occurs, it is necessary to perform a consequence analysis to evaluate potential elements at risk (environment and people). At this purpose the source terms need to be identified, which is intended as the time trend of the flow rate (or flow rates of the various phases involved, if any) at rupture point of a certain size, caused by a generic natural event, in a generic production and/or process fluid transport system in a pipeline. Approaches, from short-cut to accurate ones can be profitably used, [63,64]. Subsequently, the physical effects on the environment and people must be evaluated. The oil spilling from a buried pipeline according to the conditions of tab. 2 can generate important consequences on the surrounding community depending on the hydrocarbon transported in the pipeline. In case of liquid material (Light Non-Aqueous Phase Liquid), the potential impacts on both the environment (ground water transportation, soil contamination, etc.) and people (following the ignition of flames from pools of released liquid (pool fires, [65]) must be analyzed. In the first case, the impact of the release in terms of soil contamination can be determined by using different approaches [66,67], according also to the soil contamination limits, regulated by Dlgs. 152/06, [68]. The aquifer contamination can be quantified by using different methods, including semi-quantitative approaches by using 2D or 3D models. If the spill occurs above ground level, i.e. above the ground, the spilled fluid could flow along the terrain (unchanneled

Fig. 6. Landslides phenomena in the area of interest and pipeline position.

runoff, also known as overland spill migration), due to the intense flow and pressure that generally characterizes this type of release. For this reason, it is important to estimate the extent of the area affected by runoff and, furthermore, to determine whether this phenomenon could affect critical points or areas from an environmental safety perspective: for example, surface watercourses, lakes, protected areas, etc. Simulating this phenomenon is very complex, as the following factors must be considered in order to accurately represent the physical process taking place: (i) fluid dynamics that respect the morphology of the terrain, including any natural and/or artificial obstacles; (ii) the processes of fluid adhesion to the edges of its flow domain (e.g. the soil itself or lateral physical barriers); (iii) evaporation processes or other types of decay kinetics; (iv) partial infiltration of oil into the soil. In any case the following minimum data are necessary: (a) Digital terrain model (DEM or DTM); a cell resolution of (at least) 20 m is recommended, (b) Coefficients for estimating soil adhesion rates (e.g. Manning coefficient) and evaporation, c) External temperature and wind intensity data. Specific approaches implemented in different software can be use for the purpose, [69–71]. Other superficial effects following the material release from a above ground pipeline is the impact on watercourse, lake or sea. This scenario may arise due to a direct spill (in the case of rivers or lakes) in the event of flooding, or as an indirect consequence of a spill that has occurred on the surface (i.e. the migration into surface waters of oil fractions resulting from the runoff of a spill that has occurred on the surface). Approaches already present in the literature can be used for the purpose, [72]. Finally, the effects on people caused by a gas release must be considered. At this end short-cut and refined methods for buried and above ground pipelines can be profitably used, [73,74]. The analysis of the above-mentioned methods for the tracking oil spilling and consequence caused by a pipeline rupture will the not treated in the example of Section 3 and object of future publications.

3. Illustrative example

As illustrative example a 32-inches (812.8 mm) diameter and 16 mm thick buried pipeline with material type API 5L X60, [75]), containing pressure-stabilized oil with working pressure:p = 7.7 MPa, is herein analyzed. The pipeline is placed 3.0 m under the ground level and ideally located in the Liguria Region (Italy).

From the Idrogeo portal (https://idrogeo.isprambiente.it/app/), it has been possible to select the geographical area of interest and observe the areas subject to the main landslide movements. As can be seen from the maps shown in Fig. 6, different types of landslides are present in the area of interest: translational/rotational sliding, collapse/toppling, complex movement, rapid flow and areas with diffuse surface landslides. The horizontal path of the pipeline, following a small stream is indicated in on the left figure in blue.

In the following a particularly critical slope surface is selected (the yellow one), which is characterized by a landslide with a rotational–translational movement type, approximately 40 m wide and 70 m long, with a very large surface area (2850 m^2). A section of the pipe route lies at the foot of this slope. In Fig. 6 it is possible to observe both the detail of the critical slope surface and the position of the landslide with a translational movement towards the bed of the stream.

From the morphological study of the landslide and the effects of rainfall on the slope, it is possible to hypothesize that the main cause of triggering the landslide phenomenon may be the presence of superficial water, associated with the presence of a piezometric aquifer. The Regional Technical Map, combined with a GIS tool allowed to reconstruct the altimetric profile of the landslide. In particular, the highest and the lowest points of the landslide are at approximately 120 m and 76 m above sea level, respectively.

From a geognostic investigation campaign, consisting of piezometric and geognostic surveys, carried out along the landslide body for a depth of 20 m, it has been possible to reconstruct the stratigraphy of the slope surface at the landslide area, and to evaluate the water level and, finally, to perform the mechanical characterization of the soil.

The information obtained from the geological map and the survey campaign, allow to identify the type of soils present in the landslide area, that are essentially two: a surface blanket and a substratum. Similarly, it is assumed that the surface blanket consists of a reworked silty clay of low to medium consistency, while the substratum, located at a depth varying between 10 m and 18 m, is characterized by a consistent marl with lithoid sections. Fig. 7 show the stratigraphy of the landslide slope and the location of the pipe, respectively.

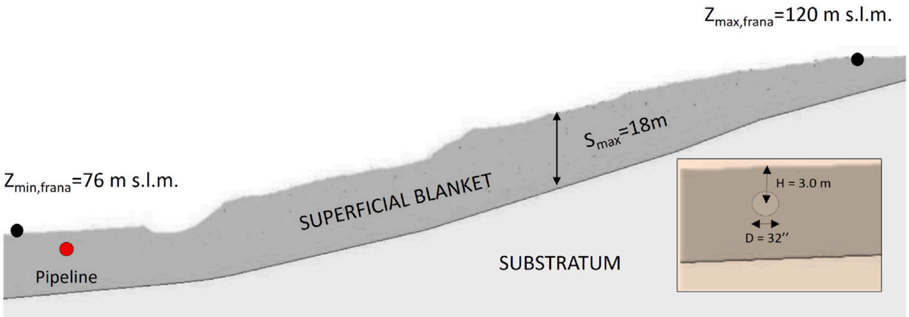


Fig. 7. Stratigraphic profile of the landslide slope.

Table 3
Soil properties.

Layer	γ [kN/m^3]	γ_{SA} [kN/m^3]	ϕ'	c' [kPa]
superficial blanket	20.7	21.6	30'	63
substratum	22.5	23.5	35'	98.1

From the shear tests conducted in the laboratory on samples of the surface blanket (slightly to medium-sized reworked silty clay) and substrate (consistent marl with lithoid sections), it has been possible to determine the geotechnical characteristics of the soils. The main characteristics are listed below. The main characteristics are listed in Table 3, where γ is the soil unit weight, γ_{SA} is the saturated soil unit weight, and ϕ' and c' are respectively the effective friction angle and cohesion of the soil.

3.1. Probability of occurrence of the landslide and PGD estimation

The landslide hazard analysis is conducted using the quantitative method, i.e. by calculating the probability of occurrence H of a landslide event in a given area A, in a given time interval t and with a given extent S, according to the formulation provided in Section 2.1.1.

From the Idrogeo portal (https://idrogeo.isprambiente.it/app/), which contains the susceptibility maps for the entire Italian territory, it has been possible to identify the susceptibility value of the landslide area under examination. A very high probability, ''P4'', is associated to the analyzed landslide, which corresponds to a probability greater than 80% that the landslide phenomenon will occur in the identified area. For the quantitative evaluation of P(S) is necessary to adopt one of the methods suggested in [29], from analytical (regression) to multivariate GIS-Based approaches. For the purpose. the results obtained recently by Orefice and Innocenti were used, [76], that for the analyzed zone and by using maximum entropy model provided a probability $P(S) \approx 0.8$.

As far as the calculation of the landslide index P(A) is concerned, reference is made to the inventory of landslide phenomena in Italy (IFFI Project) elaborated at the national level by ISPRA. As can be observed in Fig. 3(b), for the Liguria region P(A) is in the range 10%–15%. It is possible to estimate a value of the landslide index P(A) equal to 0.099 [34]. Please note that it is always possible to refer to further maps provided by the regional authorities, if available, which are the result of specific studies conducted in a given territory.

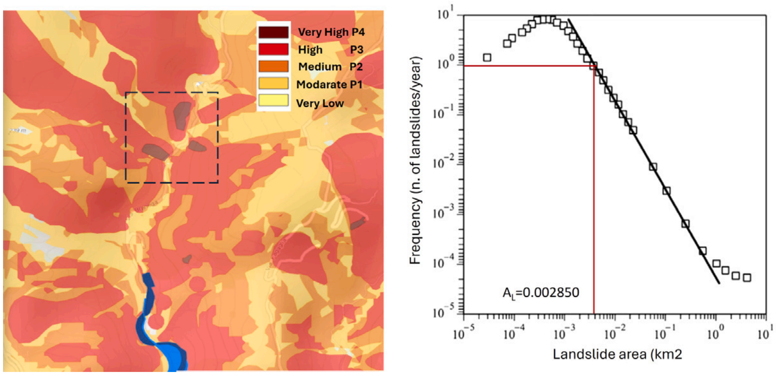
The probability of occurrence $P[N(t) > 1]$ of a landslide in a given time period t can be quantified using a Poisson distribution model, based on a historical catalogue of landslides that have occurred in the area of interest. In the case under consideration, the annual probability of occurrence of a landslide of extension $A_L = 0.002850 km^2$ is obtained by assuming the curve of Fig. 8(b)b that provides the average annual frequencies of occurrence of a landslide, [38].

Given the quantities of interest, it is possible to calculate the landslide hazard value H according to Eq. (2). Because the limited values of the probability P, this latter can be approximatively expressed as $\lambda \times t$. If the reference time is 1 year, the probability $P = \lambda$. In the present illustrative example $P = P(S) \times P(A) \times P[N(t = 1) = 1] = 0.8 \times 0.099 \times 1 = 7.92E - 2.0$ events/year.

The final step of the hazard analysis is the quantification of the Permanent Ground Deformation (PGD). Generally, there are two approaches for calculating PGD: the first is based on FEM models and the second is based on analytical methods that allow a good estimate of the deformation in a faster way. In the following, an analytical method has been used to calculate the PGD, [78], which allows the landslide's slip length to be estimated on the basis of the geotechnical characteristics of the soil, the potential energy and the energy dissipated during the slip. The kinematic model herein used is illustrated in Fig. 9.

In order to select the most critical sliding surfaces several cases have been analyzed. The one illustrated in Fig. 10 corresponds to the lowest safety coefficient (0.721). The input parameters to derive the PGD value are the following:

- Volume of the mass involved in sliding: V = 1495 m^3;
- Volume weight: γ = 20.70 kN/m^3;
- Effective internal friction angle of the soil: ϕ' = 30°



(a) (b)

Fig. 8. (a) Susceptibility map [77] (b) Hazard Curve, [38].

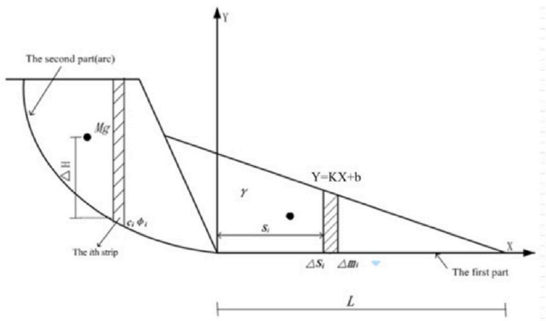


Fig. 9. Kinematic model for PGD estimation.

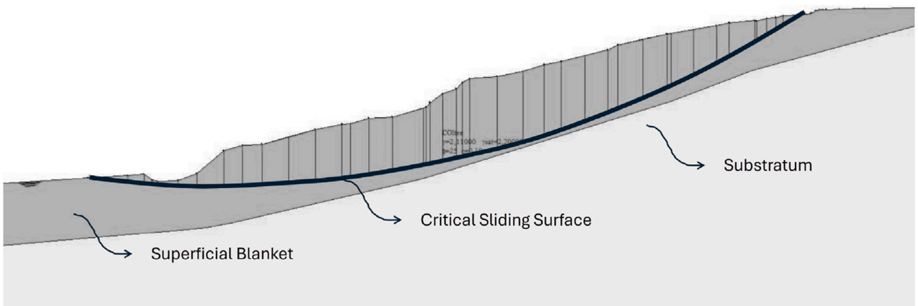


Fig. 10. Critical sliding surface for the identification of the landslide volume.

- Effective soil cohesion: $c' = 63$ kPa
- Distance between the center of gravity of the sliding surface and the surface with zero potential energy: $\Delta H = 14$ m

The method provided a particularly important value of PGD equal in this case to 22 m.

3.2. Vulnerability analysis of the pipeline and fragility curves derivation

In this section, the calculation of the vulnerability analysis of the pipeline subject to a landslide event is presented. Since there are no empirical fragility curves in the literature, the objective of the analysis reported here is to define specific analytical fragility curves for illustrative example of pipeline, considering different levels of damage and oil spilling. In what follows, the numerical model of the pipeline, the definition of limit states and the construction of the fragility curves will be presented.

Table 4
Parameters of the winkler springs.

Tu	Dt	Pu	Dp	Qu	Dqu	Qd	Dqd
(kN/m)	(mm)	(kN/m)	(mm)	(kN/m)	(mm)	(kN/m)	(mm)
204	10	745	81.3	745	162.5	2625	162.5

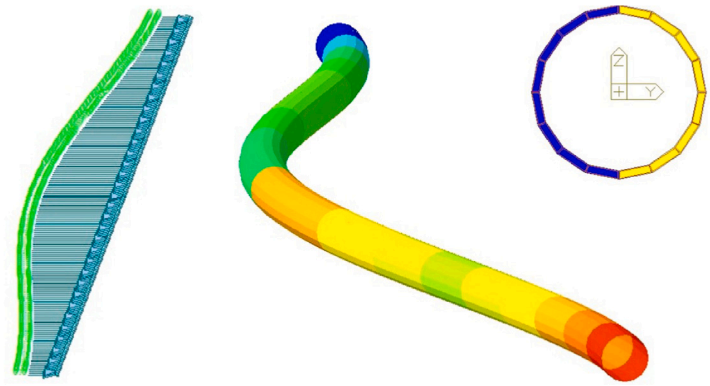


Fig. 11. Schematic of the F.E. model of the pipe.

3.2.1. Numerical modeling of the pipeline

The first step in the calculation of vulnerability of pipelines subjected to landslide events is the modeling of the pipe and the surrounding terrain. This can be performed through the use of the most common finite element software, and in this specific case, reference was made to a three-dimensional, non-linear model of the pipe, realized with the OpenSees calculation software [79]. Specifically, the pipeline was modeled with fiber elements with non-linear behavior. In addition, for greater refinement of the modeling, a finer discretization (elements with a maximum length of 0.2 m) was opted for in correspondence with the landslide zone located in the central part of the route for approximately 200 m, and a coarser discretization of approximately 0.5 m for the remaining 800 m of pipe. For the steel, reference was made to a Giuffrè-Menegotto-Pinto constitutive law, summarized in OpenSees "Steel02" material [80], (yielding strength 415 MPa, Elastic Modulus 210.000 MPa, strain hardening 1%), while for the modeling of the lateral and foundation soil (vertical and axial), perfect elasto-plastic relationship were used, whose main characteristic quantities are defined in accordance with the American ALA guidelines and reported in Table 4, [50]. Pipe and Winkler soil modeling are illustrated in Fig. 4.

Although the width of the landslide is approximately 40 m, as suggested in the scientific literature, it was decided to model a pipe path of approximately 1,000 m in length (approximately 500 m upstream and downstream from the position of the active landslide) in order to eliminate all possible boundary effects. Naturally, given the discretization operated in the model, as the axial, lateral and vertical Winkler springs are applied at the subdivision nodes between the various elements, they are much denser at the central part of the pipe at the landslide surface. Fig. 11 shows a schematic of the F.E. model, including the sinusoidal displacement profile (on the left), the beam model under deformation and the fiber section (on the right).

3.2.2. Estimation of the mean annual frequency of occurrence of oil release

In order to estimate the fragility curves associated with a certain type of oil release (LOC), it has been first necessary to recognize the limit states that are capable of generating release conditions. The conditions proposed by Jahangiri and Shakib [8], shown in Table 2, are therefore proposed. These conditions are associated either with operating limit states, for a controllable leakage, or with ultimate limit states, for a complete rupture of the pipe and an instantaneous release of the contents. In the present proposal, controllable loss is associated with a 70 mm bore and complete loss with a full-bore condition, [81]. For the calculation of the fragility curves, only limit states capable of generating releases have been considered, so that reaching a maximum deformation in the pipe of 10% will be associated with the condition of controllable release (LOC1), while reaching a deformation of 15% will be associated with the condition of instantaneous loss of all contents (LOC2).

3.2.3. Fragility curves derivation

The vulnerability of the pipeline to the landslide is expressed in terms of 'fragility curves', i.e. through curves that provide the value of the probability of damage given a measure of landslide intensity IM. In case under consideration the permanent ground displacement (PGD) will be used as IM. The construction of the fragility curve is obtained by statically applying to the non-linear 3D F.E. model of the pipeline, a profile of displacements with increasing intensity δ, which follows the following spatial distribution [9].

$$y(x) = \delta(cos(\pi x / W / sin\alpha)^n) \tag{4}$$

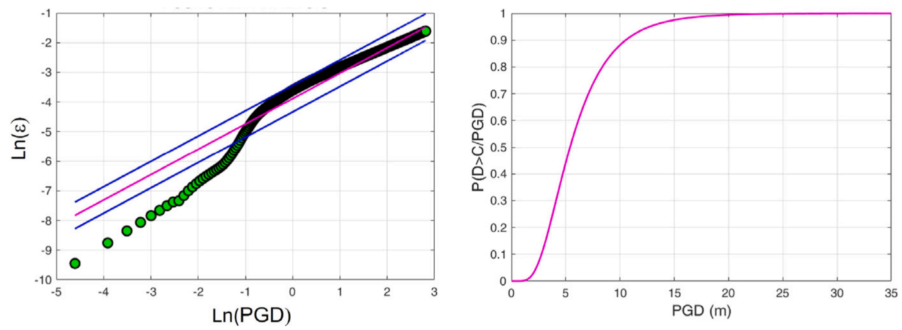


Fig. 12. Probabilistic demand model and fragility curve for LOC1.

where x is the value of the reference abscissa of the pipe, α represents the angle of inclination of the pipe with respect to the direction of the landslide and W the width of the landslide face. In Fig. 11, the displacement profile of the 3D FE model is shown, along with the deformation in the section of the pipe subjected to the landslide.

The fragility curves are calculated by implementing the results of a non-linear analysis, obtained by increasing the displacement profile, in a probabilistic model based on a linear regression performed in the log–log plane. Assuming that the deformation demand and structural limit states follow a lognormal distribution, the probability of exceeding a specific damage state can be estimated with a standard cumulative normal distribution function:

$$P(EDP > LS|IM) = 1 - \phi\left(\frac{ln(LS_m) - ln(D_M)}{\sqrt{\beta^2_{D|IM} + \beta^2_{LS}}}\right) \tag{5}$$

In which:

- ϕ is the standard normal distribution function;
- LS_m is the median estimate of the structural limit state;
- D_m is the median estimate of demand (PGD);
- $\beta_{d/IM}$ is the dispersion of demand conditional on the event intensity measure (PGD);
- β_{LS} is the structural limit state dispersion.

The median demand estimate is predicted according to the following expression:

$$D_m = aIM^b \tag{6}$$

where a and b represent the coefficients of the linear regression based on the deformation samples obtained from the non-linear pipeline analysis, whereas IM represents the values of the PGD. Assuming a lognormal strain distribution, the median demand estimate in the logarithmic plane can be assumed to be linear. The dispersion of demand conditional on PGD can therefore be estimated by linear regression according to the following expression:

$$\beta_{d|IM} = \sqrt{\frac{\sum_{i=1}^{n}\left[\ln(d_i) - \ln(D_{mi})\right]^2}{n-2}} \tag{7}$$

where n represents the number of PGD increments and i the ith sample. In order to account for the high uncertainties related to both the demand (randomness of the model, geotechnical parameters, etc.) and the structural limit state (uncertainties related to the correspondence between the deformation of the pipe and the actual release of material from the pipe), the dispersion shall be increased. Along this vein, a coefficient of variation 0.4 has been adopted in this study. Fig. 12 shows the results of the linear regression and the calculated fragility curves for the two types of controllable release (LOC1), and similarly in Fig. 13 those for instantaneous loss of all content (LOC2). The pink line of Fig. 12 represents the Eq. (6) with IM=PGD and the other two lines the bounds at ± a standard deviation. The dots in the figure on the left represents the values of ϵ derived through a pushover analysis as function of ln(PGD).

3.2.4. Derivation of the mean annual frequency of occurrence of LOC events

Once fragility curves and the value of the expected PGD have been determined, it is possible to calculate the release probability associated with the previously defined limit states. The release probability for the expected PGD both for LOC1 and LOC2 can the easily derived from Figs. 12 and 13

It can be noted that for the expected PGD, the release probability is very high for both types of release. The results obtained for the analyzed case study are the following.

$$P(\varepsilon_{PGD} > \varepsilon_{LOC_1}|PGD = 22m) = 0.99 \tag{8}$$

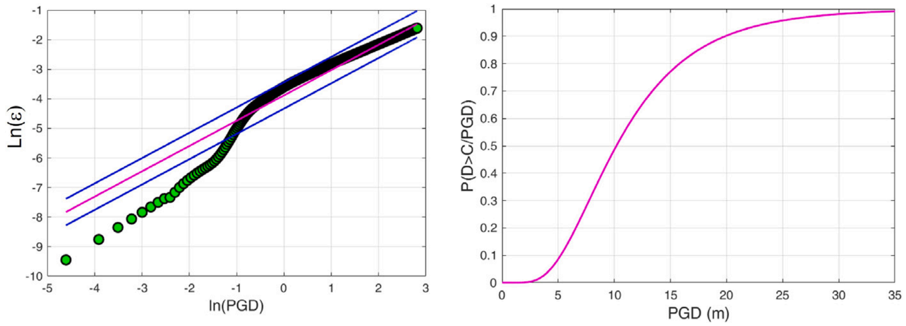


Fig. 13. Probabilistic demand model and fragility curve for LOC2.

$$P(\varepsilon_{PGD} > \varepsilon_{LOC_2} | PGD = 22m) = 0.91 \tag{9}$$

It follows that, the average annual frequency of release LOC, can be calculated by multiplying the release probability of each type of release ($LOC1$ and $LOC2$) by the value of the landslide hazard H, previously evaluated. Consequently it is possible to determine the mean annual frequency of occurrence associate to $LOC1$ and $LOC2$ as product of H and P, obtaining respectively 7.82×10^{-2} for $LOC1$ and 7.2×10^{-2} for $LOC2$.

It can be seen that the mean annual frequency of the oil spilling is very high for both types of release, which is due to both the high hazard value of the study area and the high expected PGD value of the landslide.

4. Discussion of the results

A possible extension of the performance-based risk assessment methodology to pipelines subjected to landslides was effectively and easily shown through a realistic illustrative example of pipelines for the oil transportation, ideally located in Italy. The method is based on a refined approach that is a synergic combination of geotechnical, structural and risk assessment tools. The application allowed to show up the following main relevant aspects:

- Simple available tools for the localization and identification of the mostly critical landslides as susceptibility maps were employed. In this way, it is easy to evaluate the position, type of landslide, damage potential, and, in general, any critical aspect that could pose a risk to a pipeline. In the example the Idrogeoportal, freely available online, was used without particular problems or restrictions
- The characterization of the landslide hazard and PGD was based on traditional and simplified tools. In particular, the identification of the critical surface and the landslide volume has been possible thanks to classical slope stability theory and a simple kinematic model for the PGD estimation. Landslide susceptibility P(S) and landslide index P(A) where derived by available landslide inventories and Regional databases. In the example, the idrogeoportal and the Liguria Region landside inventory were used. The high value of the probability of occurrence of the landslide and the related PGD obtained demonstrated a clear conservatism of the method. Moreover, the example has been properly selected being particularly critical and demonstrating the applicability of the proposed method also in this extreme case. Even if the adopted tools are characterized by a certain degree of conservatism, the simplicity and the rapidity of their application make them particularly suitable for a preliminary landslide risk assessment. More refined models can always be used without affecting validity of the proposed methodology.
- Pipeline modeling that includes soil–structure interaction was performed by adopting very well-known structural analysis tools, like Opensees, and standard p-y model theory, making the proposed method simple and rapid. However, the obtained result in terms of relative displacement between pipeline and soil denoted a certain excessive soil stiffness and strength. This aspect will need to be carefully investigated in the future, analyzing better the role of the modeling refinement of the soil–pipe interaction.
- The derivation of the fragility curves both in terms of probability of damage and loss of containment (oil) were built based on a non-linear model balanced between accuracy and computational sustainability. The use of a lognormal distribution for the derivation of fragility curves based on a linearized probabilistic demand model appears reasonable especially in a range of PDG > 0.4 m that is of direct interest for the risk analysis of pipelines.
- The evaluation of loss of containment (LOC), events based on a determinist relationship between damage e LOC conditions, can be considered reasonable given the goals of the proposed method that is a quantitative evaluation of the NaTech Risk. The main reason is related to the higher dispersion of the probabilistic response than failure conditions.
- The derived value of PDG and the relative probability of exceedance bring to a very high value of probability of LOC identifying a potential catastrophic condition. The reason of that is mainly related to the high criticality of the selected case study and the simplified pipe–soil interaction model adopted. This latter issue has already been discussed by other authors [7], which, using a parametric analysis, discovered that for a similar pipe dimension and a burial depth > 2.5 m and PGD, normalized to the pipe diameter D, greater than 6, the probability of failure can be actually very high, as in the analyzed case with a highly probable oil spilling and severe consequences (pollution, fire, etc.).

5. Conclusions

In this paper the application of the performance-based assessment (PBA) approach, typically adopted in earthquake engineering has been proposed to pipelines subjected landslides phenomena and illustrated through a realistic illustrative example of a pipeline for the oil transportation.

The proposed methodology is articulated in different sub steps: (1) definition of landslides hazard assessment methodologies and selection of suitable intensity measures for the quantification of mean annual frequency of occurrence (2) formulation of a PBA methodology and derivation of the fragility curves in a specific section of the pipeline by using Winkler and FE models; (3) performance of NaTech risk assessment in terms of mean annual frequency (MAF) of occurrence of specific damage conditions generating release phenomena (LOC) in pipelines. The method is a synergic use of existing approaches for landslide hazard assessment and for the quantification of pipeline vulnerabilities in case of landslides, within the framework of a PBA for a rapid quantification of the NaTech risk of pipelines.

In this particular case, it is important to evaluate the loss of content frequency due to the damage caused by the pipeline local rupture. For this reason, in the proposed methodology a deterministic relation between local damage and loss of containment (LOC) events has been adopted, which allows the quantification of the consequences in terms of pollution or the generation of physical effects like fire or explosion. These aspects have not been analyzed in the paper that has been focused on the quantification of the LOC frequency, leaving to future works the extension of the methodology, also to such phenomena.

An illustrative example of buried pipeline for oil transportation has been used to validate the proposed PBA framework. The selected pipeline section is located in a mountain region of Italy with a significant and different number of landslides, but with more frequent rotational/translational slides. The case study has been used to demonstrate the real applicability of the proposed methodology and showing the usability of standard tools and methods for landslides hazard and pipeline vulnerability assessment.

The results showed how the selected case study results particularly vulnerable when subjected to a shallow landslide action. The resulting LOC events frequency is high, which has also been confirmed in similar cases already present in the literature, demonstrating the high vulnerability of pipelines and the potential catastrophic consequences that it can generate in the community.

Despite its simplicity and ease of use, there are some aspects of the method that require particular attention. Measures of intensity other than PGD should be investigated and a comparative analysis carried out in terms of efficiency to reduce the dispersion of the response, when necessary. Furthermore, the use of Winkler-like models could generate soil–pipe interaction conditions with conservative results in terms of potential damage in the pipe. Finally, the link between damage conditions of the pipe and the material release should also be investigated, promoting the use of probabilistic models to account for the real variability of the LOC conditions with the pipe characteristics.

Nevertheless, the proposed approach allows to assess the NaTech risk of pipelines when subjected to landslides in a simple and rapid manner for a preliminary quantification of risky conditions of pipelines and the crossing community.

CRediT authorship contribution statement

Fabrizio Paolacci: Writing – original draft, Methodology, Conceptualization. **Daniele Corritore:** Writing – original draft, Investigation, Formal analysis. **Stefano Caprinozzi:** Writing – original draft, Investigation, Formal analysis. **Iacopo Borsi:** Writing – original draft, Validation. **Maria Giulia Sotgiu:** Writing – original draft, Validation. **Michele Bonuccelli:** Writing – original draft, Validation. **Marcello Mancini:** Writing – original draft, Validation, Supervision, Resources. **Vito Tonetto:** Writing – original draft, Validation, Supervision, Resources.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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