Analysis of crater formation in buried NG pipelines: A survey based on past accidents and evaluation of domino effect

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ABSTRACT

The formation of a crater by the abrupt and catastrophic rupture of a high-pressure pipeline can be highly relevant, especially when the crater uncovers other pipelines, which could undergo a domino effect with a significant increase of the consequences on people or on the environment. However, this scenario has been only partially studied in the literature. To assess the influence of the pipeline parameters on the dimensions of the resulting crater, a statistical analysis of accidental ruptures of buried natural gas pipelines that have involved the formation of a crater was carried out. Mathematical expressions are proposed to describe the proportionality relationships found, which can be very useful to support adequate separation distances in the design and construction of parallel corridors of pipelines after appropriate escalating effects are considered. Finally, detailed event trees were developed to calculate the probability of occurrence of the final outcomes, as well as the identified domino sequences, based on a qualitative and quantitative analysis of the data. The study of these accident scenarios, based on actual cases, represents a useful and needed advance in risk analysis of natural gas transportation through pipelines.

Keywords: Natural gas; Buried pipeline; Pipeline rupture; Crater formation; Domino effect

1. Introduction

High population growth and rapid industrialization around the world have led to a substantial increase in the consumption of Natural Gas (NG). Consequently, the NG transportation through high-pressure pipelines to ever-greater distances has also been increased (EGIG, 2015). According to the U.S. Energy Information Administration (EIA, 2017), the world consumption of NG increased due to rapid economic growth from 1499 billion cubic meters (BCM) in 1980 to 3476 BCM in 2014, representing an increase of 132%. To address this challenge, the gas industry usually maximizes its transport capacity by increasing the operating pressure of the system or by installing more pipelines, often parallel or crossing to existing ones. These pipelines transport gas or oil over great distances and sometimes they are closely separated between them, which imply a particular risk associated with the potential interaction of these systems (Acton et al., 2010; Wang et al., 2011). In these situations, a Loss of Containment (LOC) may affect a close pipeline or other structure located around the site of an accident, aggravating the corresponding consequences of the event. This type of events has happened in different accidents with

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severe consequences on people or with significant material and economic losses (Ramírez-Camacho et al., 2015).

Due to its physical and chemical characteristics, NG presents several risk scenarios depending on whether it is ignited or not. If it ignites immediately after the release, a jet fire will occur. If there is no ignition, the gas will disperse into the atmosphere as toxic dispersion. A flash fire or a gas cloud explosion, followed by a jet fire, is possible if the ignition is delayed. These risk scenarios also depend on the release mode (*i.e.*, full-bore rupture, leak/puncture), as well as the volume of gas released, the meteorological conditions at the time of the accident, and the characteristics of the surroundings (*i.e.*, urban, rural). Therefore, to ensure the integrity of NG pipelines, it is necessary to rigorously evaluate all possible hazardous scenarios and their consequences, mainly on people but also on the environment, because safety and environmental impact must have absolute priority over the demand of NG.

About the possible accidental scenarios that can occur as a result of buried NG pipelines, the formation of a crater by the rupture of a high-pressure pipeline has been reported by a limited number of publicly available studies. The formation of such a crater can be a relevant event, especially if it can imply a domino effect on other parallel or crossing pipelines uncovered by the initial rupture, thus increasing significantly the scale of the accident and its consequences on people or the environmental impact (Hemmatian et al., 2014).

Published research has focused on studying the crater formation mechanism and its dimensions but in underground explosions of TNT (Ambrosini et al., 2002; Ambrosini and Luccioni, 2006; Luccioni et al., 2009; Xin-zhe et al., 2013; Krishna et al., 2016). However, only a few studies have specifically focused on the formation of craters by the explosive rupture of buried pipelines. Bartenev et al. (1996) analysed accidental ruptures in the Central Asia-Centre gas pipeline system, which run from Turkmenistan via Uzbekistan and Kazakhstan to Russia. They found a direct relationship between the rupture length of the pipeline and the length of the crater. Acton et al. (2010) developed a framework based on experimental data, for determining appropriate design separation distances between buried parallel gas pipelines, including the maximum dimensions of the crater formed by pipeline ruptures. Silva et al. (2016) analysed the ruptures of underground petroleum product pipelines with the formation of a crater and proposed a model to predict the crater width as a function of the design pipeline parameters and the soil density. Laheij et al. (2017) studied the minimum distances between parallel pipelines in corridors located in the Netherlands. Recently, Amaya-Gómez et al. (2018) proposed a probabilistic prediction of the crater width and depth based on NG losses of containment in underground pipelines.

Nowadays, it is recognized the significance of historical analysis of past accidents as a source of valuable information on their main aspects (Lindberg et al., 2010; Kletz, 2011; Siler-Evans et al., 2014; Hemmatian et al., 2014; Lam, 2015; Ramírez-Camacho et al., 2017). In this paper, a historical survey of accidents in buried NG pipelines that have involved the formation of a crater was carried out with the aim of analysing the crater formation and its influence on possible domino effect scenarios. For this purpose, statistical analyses were implemented to study the influence of pipeline geometric (diameter), operating (pressure), installation (burial depth), and accident (rupture length) parameters on the dimensions of the crater. A qualitative and quantitative analysis of the data was considered to develop detailed event trees for intermediate and final events following the accidental release of NG from pipelines. These trees delineate the domino sequences after the formation of a crater and estimate the probability of occurrence of these scenarios. The study of these accident scenarios, based on actual cases, represents a useful and needed advance in risk analysis of NG transportation through pipelines.

In this paper, a set of 90 accidents related to the formation of craters involving underground NG pipelines is analysed (circumstances, crater dimensions, domino effect, final outcomes). The document is structured as follows: Section 2 describes how craters are formed. Section 3 presents the data gathered for this analysis. Section 4 describes the proposed methodology based on an exploratory analysis of the data gathered, which evaluates the influence of the pipeline parameters on the crater dimensions afterward, and the conditional probabilities once a loss of containment take place. Section 5 presents the results and discussions. Some concluding remarks are given in Section 6, and finally, future perspectives are described in Section 7.

2. Crater formation by the rupture of a buried pipeline

A crater is produced instantaneously after an explosive event takes place. The explosion causes the fracture, compaction and plastic deformation of the soil close to the pipe. The result is the formation of a bowl-shaped cavity by the displacement and ejection of material from below the ground surface. The dimensions of the crater formed will define the size of the area that would be affected. In the case of the rupture of a buried NG pipeline, the parameters that can influence the size and shape of the crater formed are those related to the pipeline itself (*e.g.*, diameter, internal pressure), and to the external conditions like the depth of burial of the pipeline and the soil characteristics (Tonelli and Aparício, 2005).

A classic crater configuration is depicted in Fig. 1. The considered crater dimensions are based on those defined by Hansen et al. (1964) and Cooper (1996). D_{ac} represents the apparent crater diameter, D_{tc} is the true crater diameter, H_{ac} is the apparent depth of the crater and H_{tc} is the true depth of the crater. Concerning the pipeline parameters, D denotes the outer diameter, B_d is the burial depth and L_r concerns to the length of rupture of the pipeline. The term "true crater" refers to the crater formed immediately after the pipeline rupture. Following the rupture, part of the ground ejected falls back into the newly-formed crater to form the "apparent crater" (final crater configuration), whilst another portion of ground, even sections of pipe, is expelled at a certain distance away from the rupture site. The true crater is deeper than the apparent crater; however, it is a hard task to make a direct physical measurement of the true crater in practice. For this reason, the measurements taken after an explosive event are those of the apparent crater.

2.1. Causes and energy involved

The formation of a crater can be caused by the abrupt and catastrophic rupture of high-pressure pipeline produced by a line failure (*e.g.*, a mechanical failure) or by the explosive ignition of accumulated gas leaking from a small hole in the pipe wall (a weld cracking, corrosion pinhole or puncture). However, the probability that the leaking gas flow through the soil enters the atmosphere and accidentally catches fire, explodes and ruptures the pipeline is very low (IGEM, 2012). Notwithstanding, if the size of the defect or puncture exceeds a certain "critical" length (in pipeline longitudinal direction), then the pipeline could rupture catastrophically and create a crater (Spoelstra and Laheij, 2011).

Whatever the cause of the pipeline rupture, the energy involved in the formation of the crater is different in each case. According to Peekema (2013), the rupture of a pipeline caused by the explosive ignition of accumulated NG leaking from a small hole would involve both the compression energy and the chemical energy of the gas. The latter will be available once the gas is present in a mixture with air (*i.e.*, sufficient oxygen) within the explosion limits, together with a source of ignition. The chemical energy available from an explosive gas/air mixture is much higher than the compression energy in the gas; however, the compression energy of the gas could be diminished or, ultimately, lost when the gas leaked from the pipeline. On the other hand, the same author affirmed that in the abrupt and catastrophic rupture of a pipeline caused by a line failure, the energy involved is only associated with the compression energy contained in the pressurized gas, which is released at the moment of rupture. In this case, the escaping gas from the ruptured pipeline could ignite, but not “explode”, so the chemical energy of the gas would contribute to the subsequent fire, but not to the explosive rupture.

Once the crater has been formed, the gas escaping from the broken pipeline may have a “scouring effect" and carry away the loose earth or the rock material that finds in its path; it could even eject huge fragments of the pipeline. In this way, the final crater could be much larger than the one formed by either of the previous causes. Therefore, the dimensions of the final crater may also depend on the kinetic energy of the spewing fluid and the duration of the scouring action (Peekema, 2013).

2.2. Domino effect possibilities

Once the initial rupture of a buried pipeline (P1) has formed the crater, the possibilities of a domino effect depend on whether a second buried pipeline (P2) lies within the crater limits or not, and whether it transports a dangerous fluid. Another important aspect is whether the gas leaking from P1 ruptured ignites or not. The different possible sequences have been summarized (Fig. 2). The final accidental scenarios of these sequences –pipe failure due to thermal impact or thermal/blast impact– have been based on the historical survey and risk analysis expertise (Ramírez-Camacho et al., 2015).

If P2 is outside the crater's limits, then it will not be damaged either by the explosive effect or thermal radiation because the surrounding soil will protect it. On the contrary, if P2 is inside the crater formed (whether totally or partially exposed), there are two possibilities for it to fail. The first refers to the possibility that the explosive effect of the rupture of P1 damages P2 (whether a puncture, a crack or a total rupture), causing its failure. In this case, if fluids releasing from both pipelines ignite, the resulting hazard would come from the thermal radiation or direct contact with flames produced by the fire. If there is no ignition, the gas will disperse in the atmosphere, and the soil will be contaminated if P2 transports another liquid.

Alternatively, if the explosive rupture of P1 did not affect P2, but the releasing gas from the ruptured P1 is ignited, there is a probability that P2 fails due to flames impingement or strong thermal radiation when P2 conveys a gas. If this pipeline conveys a gas and it is not adequately fireproofed, the probability of failure in a rather short time is very high. However, if P2 conveys a high flow at high pressure, the heat transfer coefficient to internal fluid could be sufficient to prevent a failure. If P2 conveys two-phase flow, the possibility of pipeline failure due to the high temperature reached by the pipe wall should also be considered. Conversely, if P2 conveys a liquid, it will act as a refrigerant and will cool the pipe wall avoiding its failure. In either case, the flow in P2 can be shut off if blocking valves are shut down; this again could lead to the pipeline failure.

To prevent such domino effect scenarios, safety distances between parallel and crossing pipelines and their surroundings have been proposed in standard or code practices such as that reported for natural gas and water parallel pipelines by the Energy Commission of Malaysia (clearance of >300 mm) or the ASMEB31.8 (clearance of >6 in for an underground structure) (Mohsin et al., 2014; Shi et al., 2012). Other approaches like Silva et al. (2016) suggest a 10 m separation for underground pipelines based on an analysis of historical accidents, and PEMEX (2009) recommend a minimum separation of 1 m in the same ditch.

3. Data collection and organization

Information of ruptures of buried NG pipelines that involved the formation of a crater was collected from accident databases, technical reports, and accident reports. The primary purpose of collecting the available information is to gather all disseminated data on crater accidents in the pipeline natural gas transportation industry and create a reliable database, which may be used to improve the information and understanding about the occurrence of this type of events and to analyse their main characteristics statistically. The main sources of information were:

- The Analysis, Research and Information on Accidents database (ARIA, 2015).
- The Federal Institute for Materials Research and Testing of Germany (BAM, 2009).
- The Major Hazard Incident Data Service database (MHIDAS, 2007).
- The Transportation Safety Board of Canada (TSB, 2015).
- The U.K. Health and Safety Executive (HSE, 2000, 2002).
- The U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA, 2015a).
- The U.S. National Transportation Safety Board (NTSB, 2015).

Where a record of interest was identified, the available data was stored in a database in MS Excel format included as supplementary material. Table 1 shows the fields used to organize the data, which are divided into seven blocks. The information contained refers to the identification of the accidents (date, location, characteristics, and causes), pipeline characteristics, dimensions of the craters, and consequences (injuries, deaths, evacuees). It should be noted that the analysis of the consequences of these accidents has not been the subject of this study, but rather the occurrence of a failure scenario.

Table 1
Structure of the database on accidents in NG pipelines that involved a crater formation.

Block	Data field	Type of field	Units
1. Accident identification	The ID number of the accident in the database	List	-
	Date of occurrence	Date	DD/MM/YYYY
	Location	Text	-
2. Pipeline characteristics	Diameter	Numeric	in
	Wall thickness	Numeric	in
	Grade	Text	-

Block	Data field	Type of field	Units
	Installation year	Date	DD/MM/YYYY
	Pressure	Numeric	bar
	Type of pipeline	Text	-
	Burial depth	Numeric	m
3. Crater dimensions	Length	Numeric	m
	Width	Numeric	m
	Depth	Numeric	m
	Area	Calculated	m^2
	Volume	Calculated	m^3
4. Characteristics of the accident	Rupture length	Numeric	m
	Distance to pipe fragments	Numeric	m
	Ignition	Text	-
	Flames length	Numeric	m
	Time from release to ignition	Numeric	min
	Time from release to shut-down	Numeric	min
5. Nature of accident	Causes	Text	-
6. Consequences	Deaths	Numeric	-
	Injuries	Numeric	-
	Evacuees	Numeric	-
7. References	Source of information	Text	-
	Report available	Text	-

During this analysis, the following aspects have to be considered:

- The dimensions registered in the database are those of the apparent crater; that is, the measurements taken after the rupture of the pipeline.
- In Fig. 1, the "Apparent crater diameter" parameter refers to a circular crater. In practice, however, the shape of a crater caused by the rupture of a buried pipeline may not necessarily be circular, mainly due to the axial symmetry of the pipeline and the length of the rupture. To better organize the data, two new fields were added, “Crater length” and “Crater width”, replacing the previous one.
- The "Apparent depth of the crater" parameter has been defined in the database as "Crater depth".
- The database contains more information than what is discussed here. The availability of these data can be useful for applying risk analysis tools, generating lessons learned to avoid recurrence of these accidents and identifying those accidents more likely to occur.

Relevant information for the analysis was incomplete or inaccurate in a number of the records extracted. To complete the missing data and to find new accident records, a detailed search was conducted by consulting other free-access sources that cover accidents in pipelines (*e.g.,* newspaper, articles, and websites) and checking the information thus obtained. After applying this extraction process, a collection of 90 accidents related to the formation of craters by the rupture of buried NG pipelines was obtained (see Appendix 1, Table A.1). The records collected cover the period from 1954 to 2015. To the best of our knowledge, this is the largest sample of such accidents gathered in peer-reviewed literature.

4. Proposed methodology to analyse the crater formation

Based on the 90 gathered records, this work proposed the following methodology to analyse possible relationships among the pipeline parameters and the crater dimensions. Initially, a preliminary analysis was attempted to extract trends related to the main parameters of the pipeline that determine the energy potential of the accident and causes. Therefore the pipeline diameter, the burial depth, operating pressure, and the length of rupture are compared.

Based on these parameters, the degree of relationship between the crater dimensions (dependent variables) was evaluated through a correlation and regression analyses. In one hand, the correlation study was evaluated using Pearson correlation coefficients r. Several alternatives exist to compute the Pearson correlation coefficient, but in this work, the traditional function using raw scores and means was considered (Rodgers and Nicewander, 1988). Besides its easy calculation, this correlation coefficient provides the direction of the correlation (*i.e.*, positive or negative) and supports the selection of independent variables within a linear regression analysis. However, the Pearson correlation coefficient assumes pairwise normal variables, which are linear related, and homoscedasticity (*i.e.*, similar finite variance), so the independent variables could be limited for those fulfilling these assumptions. Therefore, the Spearman correlation rank ρ was also compared to estimate the strength of the monotonic relationship between the crater dimensions and the pipeline parameters. The Spearman rank is not subjected to any assumption about the distribution of the variables, and it is invariant under monotone transformations. On the other hand, the regression model fit was initially determined based on two well-known numerical measures: the Residual Standard Error (RSE) and the adjusted R^2 statistic. The first one is an estimate of the standard deviation of the error based on the Residual Sum of Squares (RSS), and the latter is a measure of the linear relationship between the variables and the response. In addition, Confidence Intervals (CI) were considered for the obtained regression coefficients following the reported in Rencher and Schaalje (2008).

Finally, conditional probabilities are estimated based on the accident sequence of the 90 records gathered. These probabilities focus on the possibility of domino effects and the estimation of final outcomes given a loss of containment of a natural gas pipeline.

5. Results and discussion

5.1. Exploratory analysis

Diameter and type of pipeline

Fig. 3 shows the distribution of the entries in six categories, according to the nominal diameter of the pipelines involved in cratering accidents: $D < 10$ in (254 mm), $10 \leq D < 20$ in (508 mm), $20 \leq D < 30$ in (762 mm), $30 \leq D < 40$ in (1016 mm), $D \geq 40$ in, and unknown diameter. The pipeline diameter is known in 94.5% of cases (85 entries). Of these records, pipeline diameters from 20 to 40 in were the most frequently involved (70.6%, 60 entries), followed to a lesser extent by pipelines less than 20 in in diameter (22.3%, 19 entries), and more than 40 in (7.1%, 6 entries).

Fig. 3 also shows the distribution of the inputs by the type of pipeline. This information is available in 65.6% of the cases (59 entries). Most of these events (78%, 46 cases) occurred in transmission lines and, to a lesser extent, in distribution (15.2%, 9 entries), and gathering (6.8%, 4 entries) lines. This distribution can be explained and justified by the considerable length of transmission lines installed around the world, and also by the smaller diameter and lower operating pressure of distribution lines.

Pipeline burial depth (B_d)

NG pipelines are generally installed shallow under the ground for ease of installation and access during maintenance or repair activities. This approach is especially advantageous since the ground provides a convenient mode of supporting high-pressure pipelines under operating conditions, as well as to protect them from exposure to natural elements (e.g., severe weather, ultraviolet radiation) and from human-induced risks (Wijewickreme and Weerasekara, 2011). However, even in buried pipelines, an inadvertent release could endanger human life, cause damage to property or the environment or represent significant costs.

Fig. 4 represents the distribution of the burial depth of the pipes, according to their diameter and type. This information is known in 55.6% of cases (50 entries). Of these records, 52% of the pipelines were buried at depths between 1 and 2 m, while 26% were installed less than 1 m depth and 20% at a depth between 2 and 5 m. Only 2% of these records (one case) have a depth greater than 5 m. The latter case corresponds to the accident occurred on 13 February 2014 in Adair County, Kentucky (USA), where a 30-in (762 mm) NG pipeline buried at a depth of 9.1 m was ruptured, forming a crater approximately 18 m depth by 15 m width (PHMSA, 2014a).

Operating pressure (P_{op})

The operating pressure is one of the main parameters of the pipeline that determine the energy potential of the accident; however, only 73.3% (66 cases) of the cases reported this data. The information collected refers to the pressure at which the pipeline was operating at the time of the failure; however, when this data was not specified as such, the operating pressure of the system was taken into account. Fig. 5 illustrates that the trend is to operate at pressures from 40 to 70 bars (79% of known cases). It can also be observed that the operating pressure increases as the pipe diameter increases. Although the gathering, transmission, and distribution pipelines are designed and constructed to withstand much more pressure than the system could actually reach, it is a fact that the higher the pressure inside the pipeline, the more potentially dangerous it will be a loss of containment.

Rupture length (L_r)

The rupture length is a parameter that requires special attention, because, due to the axial symmetry of the pipeline, it defines the limits of the crater –mainly along– and, therefore, the possible area of destruction. This phenomenon takes place in a three-stage process (initiation of crack, propagation of it and, finally, the total rupture of the line), which is defined by the characteristics of the pipeline (*e.g.*, construction material, age) and the operating pressure. Andrews et al. (2004) point out that the combination of the operating pressure and crack opening angle can result in cracks propagating for 20 m and longer, at a speed of 200-300 m/s. The opening angle of the crack was not analysed in this study.

Fig. 6 shows the distribution of the entries according to the rupture length of the pipelines. This information is known only in 50% of the cases. Most of the ruptures ranged from 1 to

30 m (82.2%, 37 cases), followed much less frequently by lengths between 30 and 60 (11.1%, 5 cases), which agree with the indicated by Andrews et al. (2004). Only 2.2% of these records (one case) had a rupture greater than 100 m long. This case corresponds to the accident occurred on 21 February 1986 in Kentucky (USA), in which a rupture of a 30-in (762 mm) gas pipeline produced a crater of 152 m long and 9 m wide from a longitudinal rupture of 146 m.

5.2. Principal influences of the pipeline parameters on the crater dimensions

The correlation results indicate that, for a significance level of 5%, there are direct or positive relationships between the variables (see Table 2). The values in parenthesis indicate the number of records with information about the parameters, which were used to calculate the corresponding correlation coefficients. The correlation coefficients are not expected to be very high, as the crater dimensions can be simultaneously affected by more than one parameter of the pipeline. Therefore, it is possible to determine with which pipeline parameters a particular crater dimension is most closely related, although the calculated correlation coefficients are relatively low in some cases.

Table 2
Correlation matrix between crater dimensions and pipeline parameters. Pearson coefficients in the lower triangular and the Spearman rank in the upper triangular.

	Crater dimensions			Pipeline parameters			
	Length	Depth	Width	Diameter	Operating pressure	Burial depth	Length of rupture
Length	1.000 (87)	0.394	0.650	0.441	0.428	0.210	0.650
Depth	0.223 (67)	1.000 (69)	0.611	0.307	0.024	0.595	-0.104
Width	0.364 (78)	0.435 (61)	1.000 (81)	0.534	0.412	0.246	0.174
Diameter	0.241 (82)	0.256 (65)	0.454 (76)	1.000 (85)	0.459	0.234	0.340
Operating pressure	0.347 (63)	0.145 (50)	0.360 (62)	0.548 (66)	1.000 (66)	0.013	0.534
Burial depth	0.146 (48)	0.804 (37)	0.290 (46)	0.192 (50)	0.082 (43)	1.000 (50)	-0.003
Length of rupture	0.917 (44)	-0.155 (36)	-0.029 (41)	0.203 (43)	0.317 (42)	-0.013 (32)	1.000 (45)

Crater length (C_l)

The result of the crater length depicted in Table 2 suggests with r close to 0.92 ($\rho = 0.65$) that there is a high correlation between the crater length and the length of rupture. This result reaffirms the claim that this parameter of the pipeline defines the limits of the crater in the longitudinal direction. Therefore, the relationship between these two variables can be expressed as follows:

$$\mathrm{C}_l = k_1 \cdot L_r \quad (1)$$

where k_1 is a linear coefficient. Based on the available data of both variables under a least square approach, it was obtained that k_1 = 1.15 [Std. Error = 0.06] with a 95% CI [1.03, 1.27], the RSE is 11.96, and the adjusted R^2 is 0.89. This correlation factor is similar to the 1.02 reported by Bartenev et al. (1996). Although the value of k_1 calculated here does not conform to some of the values quoted in Table A.1 (*e.g.*, ID 53, 70 and 86), this inaccuracy could be explained by the fact that the expression of proportionality found does not take into account the relevant design parameters of the pipeline such as the density of the soil and the operating pressure, which is the driving force of the process.

Crater depth (C_d)

Regarding the crater depth, from Table 2 it can be deduced that the parameter with which this variable has a high correlation is the installation depth of the pipeline (r = 0.804, ρ = 0.595). This result can be explained by the fact that as the depth of the pipeline increases, so does the confinement effect and, therefore, also increase the amount of ground material that can be expelled by the energy of the gas released. In other words, as the burial depth is increased, the crater depth also increases until a maximum is reached (Cooper, 1996). According to the data analysed, the underlying depth at which the most probable maximum sizes of the crater can occur is between 0.9 and 9 m.

The relationship between these two variables can be expressed as the Eq. (2). In this case, the mean linear coefficient is k_2 = 1.90 [Std. Error = 0.12] with a 95% CI [1.65, 2.14], the RSE is 1.65 and the adjusted R^2 is 0.89. As in the previous case, there is also no perfect match of k_2 with some of the values listed in Table A.1 (*e.g.*, ID 8, 11 and 31); however, it should be noted that the inclusion of important variables such as soil density, operating pressure, and pipe diameter could contribute to improving the prediction of crater depth.

$$\mathrm{C}_d = k_2 \cdot B_d \quad (2)$$

Crater width (C_w)

Regarding the crater width, the pipeline parameter with which it presents the "highest" correlation is with the diameter (Table 2). This appreciation coincides with the result found by Silva et al. (2016), who point out that the crater width increases based on the pipeline diameter. However, since in this case, the correlation coefficient is relatively low (r = 0.454, ρ = 0.534), no precise conclusions can be drawn about the influence of this parameter on the crater width using linear correlation factors. However, a possible influence can be drawn using a monotonic transformation like a logarithmic regression. The following expression was obtained for the crater width in this case including an intercept:

$$\mathrm{C}_w = k_3 \cdot D^{\alpha} \quad (3)$$

where k_3 and α are regression coefficients associated with the intercept and the diameter, respectively. For the gathered records, it was obtained that $k_3 = 0.53$ [Std. Error = 0.39] with 95% CI [0.24, 1.14], $\alpha = 0.90$ [Std. Error = 0.13] with a 95% CI [0.65, 1.14]. For this case, the RSE is 0.47 and the adjusted R^2 is 0.42.

5.3. Multivariate regression of the crater dimensions

Despite the results drawn with linear or power law regressions with one variable, the crater dimensions would be more accurately described based on the pipeline parameters using a multivariate approach. For this purpose, logarithmic regressions were considered because some features, such as the rupture length, had wider ranges (*i.e.*, greater than 10:1). Also, logarithmic regressions would help to stabilize the variance and nonlinear performances. If Y denotes the response and X the variables evaluated, the logarithmic regression would have the general form of Eq. 4. Here β_0 is the intercept, β_i are the regression coefficients obtained from a least squares approach and ϵ is the associated error.

$$\log Y = \beta_0 + \sum_i \beta_i \log X_i \ + \epsilon \tag{4}$$

A variable selection approach was used to perform the multivariate regression based on the Best Subset Selection approach described by James et al. (2013). This selection fits separate least square regressions for each combination of independent variables (or predictor), then all the regressions are compared to identify the best one for a given number of predictors. For this purpose, the R-project function *regsubsets* was implemented (James et al., 2013).

Once the best predictors are selected, the best regressions were obtained based on the minimum RSE, maximum adjusted R^2, and modified versions of the Akaike Information Criteria (AIC) and the Bayesian Information Criteria (BIC) previously used by Amaya-Gómez et al. (2018). In what follows, the best regressions are described in more detail, which in all cases omit the intercept in Eq. 4. In addition, the regression assumptions are evaluated using their diagnostic plots, *i.e.*, the residuals vs. fitted values, the quantile-quantile (*q*-*q*) plot, and the regression leverage, *i.e.*, observation with unusual value in the independent variables (*i.e.*, predictor). Also, an outlier diagnosis was implemented to evaluate if any register should be removed. Therefore, the studentized residuals were considered to identify possible outliers, which corresponds with the residual errors divided by their standard error. According to James et al. (2013), the observations whose studentized residuals are greater than 3 (absolutely) are possible outliers.

Crater length (C_l)

The Best Subset selection established that the predictors that better describe the crater length were the rupture length and the pipeline diameter. The following regression was obtained:

$$\mathrm{C}_l = L_r^{\beta_1} \cdot D^{\beta_2} \tag{5}$$

where β_1 is 0.37 [Std. Error 0.07] with a 95% CI [0.22, 0.52], β_2 is 0.71 [Std. Error 0.06] with a 95% CI [0.59, 0.83], the RSE is 0.46, and the adjusted R^2 is 0.98. The logarithmic multivariate regression decreases the RSE significantly (from 11.96 to 0.46) and increases slightly the adjusted R^2.

Regarding the regression assumptions, Fig. 7a indicates that some records affect the pattern of the red line, but overall it has a flat tendency confirming the linearity assumption. Fig. 7b illustrates that the majority of residuals lie in the diagonal, which overall satisfies the normality assumption. Fig. 7c shows a moderate dispersion, which suggests that the independence assumption could be satisfied, but in general, more records are required. Finally, the regression presents low leverage as can be noted in Fig. 7d and the absolute studentized residual is less than 3, which indicate that there is not substantial evidence for the presence of outliers. Based on the aforementioned, the regression assumptions are overall satisfied.

Crater depth (C_d)

According to the results of the Best Subset, the variables with a better prediction of the crater depth were the rupture length, the burial depth, and the pipeline diameter, obtaining the following expression:

$$C_d = L_r^{\beta_3} \cdot {B_d}^{\beta_4} \cdot D^{\beta_5} \quad (6)$$

where β_3 is -0.14 [Std. Error 0.07] with a 95% CI [-0.29, 0.016], β_4 is 0.27 [Std. Error 0.14] with a 95% CI [-0.016, 0.55], β_5 is 0.48 [Std. Error 0.07] with a 95% CI [0.33, 0.63], the RSE is 0.36, and the adjusted R^2 is 0.93.

The diagnostic plots for this regression shown in Fig8 indicate that the linearity assumption is satisfied except for a couple of records (Fig. 8a), that the residuals follow a normal distribution (Fig. 8b), and that the residuals are mostly equally spread (Fig. 8c). This last result suggests that the variance does not change drastically along the fitted values and the data are independent. Finally, there is not significant leverage (less than 0.4), and the studentized diagnosis lies within -2.16 and 1.60, so there is not strong evidence about outliers, which in turn, confirm the regression assumptions.

Crater width (C_w)

For the crater width, the Best Subset selection identifies the pipeline diameter and the burial depth as the parameter that better predicts this crater dimension. The following expression was then obtained:

$$C_w = D^{\beta_6} \cdot B_d^{\beta_7} \quad (7)$$

where β_6 is 0.71 [Std. Error 0.028] with a 95% CI [0.65, 0.77], β_7 is 0.20 [Std. Error 0.14] with a 95% CI [-0.085, 0.49], the RSE is 0.44, and the adjusted R^2 is 0.97.

Despite some records have a slight high residual from the regression predictions, the diagnostic plot in Fig. 9 confirm the regression assumptions regarding the linearity (red line almost flat), the normality of the residuals, independence and homoscedasticity. Also, Fig. 9d shows low leverage, and the studentized lied in the range from -2.43 to 2.68, which indicate that there is not enough evidence for outliers.

5.4. Conditional probabilities

The different accidental sequence can follow after the release of NG from a pipeline. For instance, depending on if an immediate or delayed ignition takes place, a jet fire, flash fire or a vapour cloud explosion (VCE) may occur. Detailed event trees have been developed to provide the conditional probabilities of occurrence of the final events after the rupture of a pipeline and the formation of a crater, as well as of the domino effect.

Final outcomes

From the event tree set up for these accidents as shown in Fig. 10, it can be seen that the immediate ignition is not very likely, showing a probability of 0.344. Bubbico et al. (2016) provide an average value of 0.341 for the immediate ignition probability of compressed gases (with the weights being the fraction of cases of catastrophic and full-bore ruptures releases), which matches the value just found correctly.

For releases when the cloud dispersion is almost certain (50 cases out of 90 characterized by the “no immediate ignition” option), a median delayed ignition probability of 50% is observed; furthermore, the probability of flame front acceleration is higher (80%). In contrast to the case of the immediate ignition probability, the obtained probabilities for delayed ignition and explosion based on the reported data are higher than those cited by Bubbico et al. (2016); that is, 0.464 for delayed ignition and 0.641 for flame front acceleration.

Table 3 reports the overall probabilities of occurrence of the possible final events after the release of NG. It must be observed that since some of the final events can happen simultaneously, the probabilities can amount to more than 1.

Table 3
Overall probabilities for each type of final event.

Final event	Overall probability
Jet fire	0.544
Fireball	0.100
Flash fire	0.055
Vapour Cloud Explosion	0.223
Dispersion	0.278

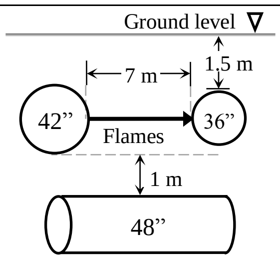
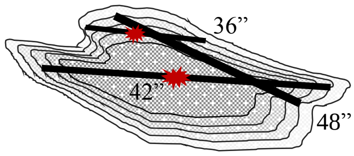
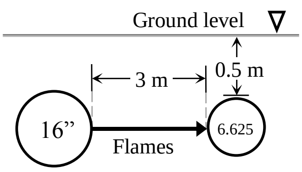
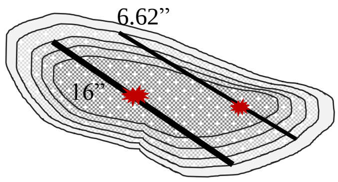
According to Table 3, in little less than a third of all the cases (specifically 27.8%), there were no dangerous consequences. Among the dangerous events, the jet fire is the most likely scenario (54.4% of occurrence), compared to 22.3% of a VCE or a 10% of a fireball, deriving either from an immediate ignition of the release, or generated by another preceding dangerous event like a flash fire or a VCE.

Domino effect sequences

Of the 90 accidents that involved the formation of a crater, in 31 of these accidents there was at least a second pipeline parallel to the failed pipeline. From these events, the probability of domino effect by the formation of a crater in parallel pipelines was estimated. The results are shown in the event tree of Fig. 11; this results should be taken with caution, as the number of cases is certainly reduced.

According to Fig. 11, there is a high probability (0.806) that a second parallel pipeline does not fall within the limits of the crater after the initial rupture, *i.e.*, that it is not affected either by the explosive effect or by the thermal radiation in case of fire. From the cases within the crater limits, none of them failed for the explosive rupture of the first pipeline, which indicates that the probability that the exposed pipeline would be affected by the explosive rupture is negligible. This figure also illustrates that in all the cases in which a secondary pipeline was exposed, the gas releasing from the source pipe was ignited. From the six cases exposing a secondary pipeline, only one of them present a flame impingement at the second pipe, which would imply a conditional probability of 0.167, and a failure due to thermal impact. If the flames do not impinge directly on the exposed pipeline, the probability of failure would be close to 0.2 if it receives strong thermal radiation. The overall probability that a second pipe located inside the crater will fail due to the thermal impact of the first ruptured pipe is low. No significant conclusions can be drawn from the statistical point of view at the moment. However, the possibility of occurrence of a domino accident should not be ignored. Table 4 summarizes the information of the identified crater accidents that involved a domino effect in parallel pipelines.

Table 4
Crater accidents with a domino effect in parallel NG pipelines.

Date Place	Pipeline 1	Pipeline 2	System configuration	Crater configuration
	Diameter / Burial depth / Pressure / Rupture length			
29/07/1995 Rapid City, MB, Canada (TSB, 1997; HSE, 2000)	42-in / 1.5 m / 60.7 bar / 10.5 m	36-in / 1.5 m / 60.7 bar / 8.5 m		
28/06/2012 Buick, BC, Canada (TSB, 2013a)	16-in / - / 66.6 bar / 17 m	6.62-in / - / 8.7 bar / 0.45 m		

In the accident in Rapid City, Canada (1995), one of the six NG pipelines that make up the system failed. The ruptured occurred in the 42-in (1067 mm) gas pipeline as a result of stress corrosion cracking. The explosive event created a crater of 51 m length, 23 m wide and 5 m deep, which left exposed the 36-in (914 mm) pipeline installed at the same depth, but a 7 m distance (less than the company`s horizontal spacing standard). The heat overload, produced by the fire of the gas releasing from the first pipeline, caused the rupture and ignition of the 36-in (914 mm) pipeline. A third 48-in (1220 mm) pipeline, passing under the location of the first and second pipeline ruptures, was exposed to the fire but did not fail. The remaining three pipelines were not affected, as they did not fall within the crater limits. One person was injured, and the fire consumed 19,600 m^3 of NG.

In the accident near Buick, Canada (2012), a rupture and ignition occurred on a 16-in (406 mm) gas pipeline due to a pre-existing hook crack. Prior to the rupture, this pipeline experienced a gradual pressure increase due to the accumulating gas when the system was temporarily shut down. The elevated pressure was sufficient to rupture the pipe along the longitudinal seam starting at the location of the pre-existing hook crack. A large crater was created (17 m long, 7.6 m wide and 1.1 m deep) that exposed the 6.62-in (168 mm) gas pipeline located nearby in the same right-of-way, but without damaging it. Approximately 25 minutes later, this pipeline, which had also been shut down, ruptured as a result of overheating due to fire impingement, and the escaping gas also ignited contributing to feeding the fire. At the time of the ruptures, both pipelines contained pressurized sour gas. The fire consumed 961,400 m^3 of NG, and 1.6 hectares of land were burned.

Based on the information from both accidents, the regressions from Eq. (1) to Eq. (3) for the univariate approach, and Eq. (5) to Eq. (7) for the multivariate approach, preliminary predictions of the crater dimensions were estimated (Table 5). Note that the burial depth of the pipelines in the Buick accident was not reported, so for comparison purposes, they are assumed as a cover of 3 ft. (0.91 m), which is commonly implemented (ASME, 2002). The preliminary predictions show interesting results of the crater width and depth, bearing in mind that the reported dimensions account the effects from the two failures, whereas these predictions consider them separately. For more in-depth analyses of these accidents, please refer to the approach proposed in Amaya-Gómez et al. (2018). The records and correlation factors proposed in this paper can be used to identify preliminary domino effect scenarios based on some *safety distances*. For these cases, a rupture centered at P1 would uncover P2 because the half of predicted width is greater than the separation between the two pipelines (*i.e.,* 12.77 m for Rapid City and 5.01 for Buick accidents).

Table 5
Comparisons of the predicted confidence intervals of the craters for the domino effect cases for the univariate and multivariate regressions.

Event	Pipe	D (in)	B_d (m)	L_r (m)	Univariate prediction			Multivariate prediction		
					C_l (m)	C_d (m)	C_w (m)	C_l (m)	C_d (m)	C_w (m)
Rapid City**	P1	42	1.5	10.5	(10.82 – 13.37)	(2.48-3.20)	(27.86-30.73)	(28.05–41.61)	(3.99-6.01)	(12.68-18.59)
	P2	36	1.5	8.5	(8.76 – 10.82)	(2.48-3.20)	(23.89-26.34)	(23.32-34.37)	(3.81-5.74)	(11.46-16.54)
Buick***	P1	16	0.91*	17	(17.52 – 21.65)	(1.51-1.95)	(10.61-11.70)	(17.01-24.80)	(2.09-3.02)	(5.88-8.36)
	P2	6.62	0.91*	0.45	(0.46 – 0.57)	(1.51-1.95)	(4.39-4.85)	(2.06-3.98)	(1.80-4.10)	(3.30-4.25)

*Assumed as 3 ft. ** $C_l = 51$m, $C_d = 5$m, and $C_w = 23$m. ***$C_l = 17$m, $C_d = 1.1$m, and $C_w = 7.6$m.

Nevertheless, safety distances in domino effect scenarios depend on the escalating effects from the primary system (Alileche et al., 2015), so these separations should consider the minimum distance at which escalating events are avoided. In the case of natural gas, they will be delimited by the extension of the flame envelope (Flash Fire); the flame length and its direction (Jet Fire); or the overpressure associated with the explosion energy (VCE) (Alileche et al., 2015). Therefore, further analyses are required to estimate a safe distance as the approaches reported in Sklavounos and Rigas, 2006 and Mohsin et al. (2014) for Jet Fire scenarios, which are the most probable events.

6. Conclusions

Failures of buried pipelines are accompanied by the formation of a crater that may pose risks to the surrounding people and environment. The crater may expose parallel or crossing pipelines, which in turn, could trigger a domino effect scenario. Considering the NG increasing relevance in pipelines, a database of 90 real accidents was gathered to study possible prediction parameters for the crater dimensions. The database attempts to reduce this existing gap for the natural gas transport by pipeline. Until now, a complete record of crater accidents occurred in this type of facility has not been found. The data collected serve as a reference and contributes to keeping understanding the hazards and evaluating risks in the transport of natural gas through pipelines.

Despite the limited number of records obtained, linear relationships could be determined for the length, depth, and width of the crater. Also, conditional probabilities were determined once a loss of containment is assumed for buried pipelines, including the possibility of a domino effect scenario. The analyses of the data suggest that most pipes were installed at a depth from 1 to 2 meters (about 52%); pipelines tended to operate at high pressures (between 50 and 70 bars), and the most likely length of a pipe rupture varied between 1 and 30 meters.

Data analysis allowed us to obtain relationships to describe the influence of the pipeline parameters (which also determine the energy potential of the rupture) on the dimensions of the resulting crater. According to the cases analysed, the length of the crater caused by the rupture of a pipe is linearly proportional to the length of the break by a correlation factor of 1.15. Similarly, the depth of the crater is linearly proportional to the installation depth of the pipe by a correlation factor of 1.89. Regarding the width of the crater, it was found that the diameter of the pipe is the parameter with which it has a more significant correlation; in this case, the correlation factor obtained is 0.68 in a power law expression.

The conditional probabilities of the branches of the post-accident event trees associated with NG have been calculated from historical records; due to the reduced number of cases, these results should be taken with caution. The overall probability of a safe conclusion (but implying a certain environmental impact) for an accidental release is about 30%. A jet fire represents the most dangerous final event, with an occurrence probability close to 55%. Outcomes characterized by large impact areas, such as VCE, fireballs and flash fires, are less likely.

Although the number of domino accidents identified in parallel pipelines has been low, the intuitive hypothesis that the formation of a crater may lead to a domino effect has been quantitatively confirmed. According to the data found in the literature, there is a probability in parallel pipelines of 0.194 that a second pipeline is inside the crater and, therefore, that it is subject to a certain risk of a domino effect. In this case, the probability of a pipeline being affected (*i.e.,* broken) by the thermal load generated by the fire of the initial rupture is 0.064. While this probability is low, the reader should bear in mind that this analysis does not consider the effect of the soil in the crater predictions (this aspect will be investigated in future studies), so the occurrence of a domino accident should not be ignored.

7. Future directions

The results obtained can be beneficial to establish adequate separation distances in the design and construction of parallel pipes. Indeed, the objective is to avoid any damage to other pipes in case the rupture of one of them implies the formation of a crater and, consequently, being able to avoid the domino effect, so interesting approaches like the reported by Nessim et al. (2004) can be used to support the design and assessment of onshore NG pipelines.

Nomenclature

B_d	Pipeline burial depth, m
C_d	Predicted crater depth, m
C_l	Predicted crater length, m
C_w	Predicted crater width, m
D	Pipeline outer diameter, in
D_{ac}	Apparent crater diameter
D_{tc}	True crater diameter
H_{ac}	Apparent depth of the crater
H_{tc}	True depth of the crater
k_1	Length linear regression coefficient
k_2	Depth linear regression coefficient
k_3	Width linear regression coefficient associated with the regression intercept
L_r	Length of rupture of the pipeline, m
P_{op}	Pipeline operating pressure, bar
R^2	Coefficient of determination
r	Pearson Correlation coefficient
α	Correlation factor associated with the pipe diameter
β_i	Multivariate regression coefficients
ΔH	Difference between the depth of the true crater and the apparent crater.
ρ	Spearman correlation rank

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Appendix

Table A.1.
Domino effect in NG pipelines involving the formation of a crater.

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[a] (m^2)	Volume[b] (m^3)								
1	17/01/1954 Toledo, OH, USA	16 / - / - / - / T / 27.6 / -	18.3	2.4	3	35	276	- / -	No	None	- / 30	MF	0 / 0 / -	-	Toledo Blade, 1954
2	18/06/1961 Laurel, MS, USA	36 / - / - / - / T / - / -	9.1	9.1	6.1	65	1060	- / 183	Yes	-	- / -	-	10 / 0 / -	-	Evening Independent, 1961
3	19/11/1961 Warrenton, VA, USA	- / - / - / - / - / - / -	12	3	1.8	28	136	12 / 137	Yes	-	- / -	-	0 / 0 / -	-	St. Joseph Gazette, 1961
4	04/03/1965 Natchitoches, LA, USA	24 / 0.25 / X46 / - / - / 54.6 / 1	23	9	4.5	163	1950	8.2 / 107	Yes	-	Immediate / 45-60	C	17 / 9 / -	-	HSE, 2002; MHIDAS, 2007
5	22/02/1973 Austin, TX, USA	10.8 / 0.373 / - / - / - / 36.9 / 1	3.05	3.05	-	7.3	-	- / No fragments	Yes	-	10-15 / 22	MF	2 / 6 / -	-	HSE, 2002
6	02/01/1974 Illinois, USA	22 / - / - / - / T / - / -	18.3	-	4.6	-	-	- / -	Yes	45	- / -	-	- / - / -	-	Star-News, 1974
7	02/03/1974 Monroe, LA, USA	30 / 0.438 / X52 / - / T / 56 / 1.95	30	9.1	7.6	215	4346	12 / -	Yes	-	Immediate / 85	MF	0 / 0 / 0	-	HSE, 2002
8	15/03/1974 Farmington, NM, USA	12 / 0.25 / - / - / T / 34.9 / 0.76	13	5.2	3	53	425	2.4 / 30	Yes	100	8 / 75	C	0 / 3 / 0	-	HSE, 2002
9	21/05/1974 Meridian, MS, USA	6.6 / 0.071 / - / 1970 / G / 21.1 / 0.9	3	3	1.8	7	34	- / No fragments	Yes	100	20 / -	C	0 / 6 / -	-	MHIDAS, 2007
10	09/06/1974 Bealeton, VA, USA	30 / 0.312 / X52 / - / T / 50.5 / 1	36	11	2.1	310	1740	17 / 91	Yes	-	Immediate / 55-105	C	0 / 0 / 0	-	HSE, 2002
11	09/08/1976 Cartwright, LA, USA	20 / 0.25 / - / 1949 / T / 54.1 / 0.6	13.7	7.6	3.05	82	665	- / -	Yes	60	Immediate / 40-60	TPA	1 / 6 / -	-	HSE, 2002

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
12	01/11/1978 Tabasco, Mexico	21 / - / - / - / D / - / -	91.4	-	6.1	-	-	- / -	Yes	-	- / -	MF	11 / 52 / -	-	MHIDAS, 2007
13	11/11/1979 Monroe, LA, USA	20 / - / - / - / T / - / -	21.3	21.3	6.1	355	5796	- / -	No	None	None / -	-	0 / 0 / Yes	-	Daily Kent Stater, 1979
14	04/11/1982 Hudson, IA, USA	20 / 0.281 / X52 / - / T / 57.7 / 0.9	19.5	15	2.75	230	1685	19.2 / 13.7	Yes	100	Immediate / 65	TPA	0 / 5 / -	X	BAM, 2009; HSE, 2002
15	25/03/1984 Eltersdorf, Germany	28 / 0.276 / DIN 2470 / - / T / 67.5 / 1	30	30	6	707	11310	10 / -	Yes	100	- / -	-	- / - / -	-	HSE, 2000;
16	31/03/1984 Kouřim, Czech Republic	- / - / - / - / D / - / -	4.6	4.6	-	17	-	- / -	-	-	- / -	-	- / - / -	-	MHIDAS, 2007
17	25/11/1984 Jackson, LA, USA	30 / 0.311 / X52 / 1955 / T / 71.4 / 0.9	27.5	7.6	3	164	1310	- / -	Yes	100	Immediate / Immediate	TPA	23 / 5 / -	X	HSE, 2002
18	10/03/1985 Ignace, ON, Canada	36 / 0.36 / - / - / - / 66.5 / -	27	10.6	3	225	1800	22.5 / -	Yes	-	- / -	-	- / - / -	-	HSE, 2002; BAM, 2009
19	27/04/1985 Beaumont, KY, USA	30 / 0.469 / X65 / 1952 / T / 69.7 / 1.8	27.5	11.6	3.7	250	2470	9 / -	Yes	-	Immediate / 146	C	3 / 5 / -	X	HSE, 2000
20	20/08/1985 Lowther, ON, Canada	36 / 0.36 / - / - / - / 67.9 / -	28	-	4.9	-	-	9.4 / 320	Yes	-	- / Immediate	C	- / - / -	-	HSE, 2002
21	21/02/1986 Lancaster, KY, USA	30 / 0.375 / X52 / 1957 / T / 69.4 / 1.8	152	9.1	1.8	1085	5215	146 / -	Yes	-	Immediate / 40	C	8 / 0 / 77	X	HSE, 2000
22	02/03/1986 Callander, ON, Canada	36 / 0.36 / - / - / - / 62.6 / -	31	-	4	-	-	31 / 185	No	None	None / -	-	- / - / -	-	HSE, 2002
23	06/06/1990 Marionville, ON, Canada	12.7 / 0.252 / 5LX / 1957 / - / 47 / 1.2	4.6	1.5	1.7	5.5	25	- / No fragments	No	None	None / 165	TPA	0 / 0 / Yes	-	HSE, 2002
24	15/01/1991 Cochrane, ON, Canada	30 / 0.36 / - / - / - / 63.1 / -	49	33	7	1270	23700	25.5 / -	No	None	None / 8	C	- / - / -	-	HSE, 2002
25	08/12/1991 Cardinal, ON, Canada	20 / 0.252 / - / - / - / 63.4 / -	17.8	9	2.7	126	906	25.7 / 20	No	None	None / 35	C	- / - / -	-	HSE, 2002

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
26	15/07/1992 Potter, ON, Canada	36 / 0.36 / Polyethylene / 1973 / T / 69 / 0.9	56.1	13.6	4.5	600	7190	46.8 / 250	Yes	-	- / -	C	- / - / -	-	HSE, 2002; MHIDAS, 2007
27	22/12/1993 Moffat, Scotland	36 / 0.752 / - / - / T / 48 / 3	10	10	4	80	838	- / -	No	None	None / -	MF	0 / 0 / Yes	-	MHIDAS, 2007; BAM, 2009
28	05/02/1994 Tabasco, Mexico	24 / - / - / - / - / - / -	200	-	7	-	-	- / -	Yes	-	- / -	OHE	30 / 8 / 500	-	MHIDAS, 2007
29	15/02/1994 Maple Creek, SK, Canada	42 / 0.427 / X70 / 1982 / T / 83.2 / 1.5	22	-	-	-	-	21.9 / 125	Yes	-	Immediate / 120	MF	0 / 0 / 0	X	HSE, 2000
30	23/03/1994 Edison, NJ, USA	36 / 0.675 / X52 / 1960s / T / 68.2 / 3.7	43	20	4.3	675	7745	23 / >244	Yes	-	Immediate / 150	TPA	112 / 0 / 1500 fam	X	HSE, 2000
31	23/07/1994 Latchford, ON, Canada	36 / 0.36 / X65 / 1972 / - / 69 / 0.9	36	16	4	452	4826	21.8 / -	Yes	-	- / 4-38	C	0 / 0 / 0	X	HSE, 2000
32	12/07/1995 Ukhta, Russia	56 / - / - / - / T / - / -	15.3	15.3	4.9	184	2400	- / -	Yes	-	- / -	-	- / 12 / -	-	MHIDAS, 2007
33	29/07/1995 Rapid City, MB, Canada	42 / 0.371 / X65 / 1973 / - / 60.7 / 4	51	23	5	920	12280	10.5 / 90	Yes	-	Immediate / 22	C	1 / 0 / -	X	TSB, 1997
34	15/04/1996 St. Norbert, MB, Canada	34 / 0.5 / 5LX / 1965 / D / 50 / 1.3	17	13.5	5	180	2403	6.3 / 40	Yes	-	14 / 44	MF	0 / 0 / 1 family	X	HSE, 2000
35	12/07/1996 Sermenevo, Russia	- / - / - / - / - / - / -	8	8	2	50	270	- / -	Yes	-	- / -	-	0 / 2 / 0	-	MHIDAS, 2007
36	19/08/2000 Carlsbad, NM, USA	30 / 0.335 / X52 / 1975 / T / 47 / 2.1	34.4	15.5	6	420	6700	14.9 / 87.5	Yes	-	Immediate / Immediate	C	0 / 12 / 0	X	NTSB, 2003
37	07/12/2000 Jal, NM, USA	16 / - / - / - / - / - / 1	8	7	3	45	352	- / -	Yes	-	Immediate / -	-	0 / 0 / -	-	HInt Dossier, 2005
38	02/02/2001 Kamenné, Slovakia	- / - / - / - / - / - / -	38	20	10	560	15920	28 / -	No	None	- / -	-	- / - / -	-	MHIDAS, 2007

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
39	22/03/2001 Weatherford, TX, USA	12 / - / - / 1979 / - / - / 2	5	5	-	20	-	- / -	Yes	-	- / -	-	0 / 0 / -	-	HInt Dossier, 2005
40	15/03/2002 Iron C., MI, USA	36 / 0.375 / X65 / 1968 / T / 51.7 / 2	36.6	9.1	9.1	262	6350	24.4 / -	No	None	None / -	-	0 / 0 / 0	X	DOT, 2002
41	11/06/2002 Easton, CA, USA	16 / - / - / - / - / - / 1.3	10	10	6	80	1260	- / -	Yes	-	- / -	TPA	0 / 0 / -	-	HInt Dossier, 2005
42	30/11/2002 Brunswick, GA, USA	8 / - / - / - / D / 17.2 / -	3	3	1.5	7	28	- / -	No	None	- / -	-	- / - / -	-	HInt Dossier, 2005
43	02/02/2003 near Viola, IL, USA	24 / 0.312 / X52 / 1949 / D / 56 / -	-	12	7.6	-	-	4.6 / 275	Yes	90	- / -	-	0 / 0 / 15 families	-	MHIDAS, 2007; BAM, 2009
44	23/03/2003 Eaton, CO, USA	24 / 0.25 / X60 / 1978 / T / 56 / 3.7	30.5	15	6	360	5750	30.5 / -	Yes	-	- / -	-	0 / 0 / 3 families	-	BAM, 2009
45	01/05/2003 Pierce C., WA, USA	26 / 0.281 / - / 1957 / T / 43.6 / 1	30.5	6.1	3.7	146	1442	14 / 76.2	No	None	None / 90	C	0 / 0 / Hundreds of homes	-	MHIDAS, 2007
46	13/12/2003 Toledo, WA, USA	26 / 0.281 / - / 1957 / T / 35 / 1	-	15.4	-	186	-	- / -	No	None	None / -	C	0 / 0 / 4 families	-	HInt Dossier, 2005
47	25/03/2004 Woodward, IA, USA	16 / - / - / - / - / 55.2 / -	9.1	4.6	-	33	-	- / -	Yes	100	- / -	TPA	0 / 0 / 0	-	MHIDAS, 2007
48	30/07/2004 Ghislenghien, Belgium	40 / 0.512 / - / 1991 / T / 80 / 1.1	10	10	4	80	840	- / 150	Yes	-	45 / -	TPA	132 / 24 / -	X	BAM, 2009
49	12/04/2005 Jefferson, AR, USA	- / - / - / - / T / - / -	12	6.7	0.6	63	100	- / -	No	None	- / -	-	- / - / -	-	MHIDAS, 2007
50	30/06/2005 Douglas C., KS, USA	20 / 0.312 / - / 1929 / T / 36-47 / 0.6	6.1	6.1	-	30	-	4.6 / 45.7	No	None	None / 110	MF	0 / 0 / 4	X	PHMSA, 2012a
51	01/12/2005 Chicago, IL, USA	20 / - / - / - / D / - / 1.8	30.5	-	7.5	-	-	- / -	No	None	None / -	-	10 / 0 / -	-	Chicago Tribune, 2005
52	19/12/2006 Cass C., MI, USA	24 / - / - / 1950s / D / 55.2 / 1	24.4	24.4	-	470	-	1.2 / -	No	None	None / -	TPA	0 / 1 / 0	X	MIFACE, 2007

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
53	12/03/2007 Württemberg, Germany	6 / - / - / - / - / 70 / -	5	2	2	8	42	- / -	Yes	-	- / -	-	1 / - / -	-	BAM, 2009
54	25/08/2008 Pilot Grove, MO, USA	24 / 0.281 / X48 / 1937 / T / 55.2 / 1.8	15.2	10	2.2	120	700	8.5 / 91.5	No	None	None / 39	C	0 / 0 / 0	X	DOT, 2008
55	14/09/2008 Appomattox, VA, USA	30 / 0.344 / X52 / 1955 / T / 55.1 / -	23	11.3	4.6	204	2504	- / -	Yes	-	- / -	-	5 / 0 / 23 families	X	PHMSA, 2008
56	01/04/2009 Căușeni, Moldova	48 / - / - / 1970s / T / - / 2	100	-	5	-	-	- / -	Yes	50	- / -	-	- / - / -	-	European Commission, 2009
57	04/05/2009 Palm City, FL, USA	18 / 0.25 / X52 / 1959 / T / 58.9 / 1.1	35.5	5.2	2.8	145	1083	32.3 / 7.6	No	None	None / 120	C	3 / 0 / Yes	X	NTSB, 2013
58	05/05/2009 Rockville, IN, USA	24 / 0.312 / B / 1940 / T / 54.6 / -	18	8.5	-	120	-	- / -	Yes	-	- / -	C	0 / 0 / 49 families	X	DOT, 2009
59	10/05/2009 Moscow, Russia	36 / - / - / 1976 / - / - / 2.5	10.5	5	-	41	-	- / -	Yes	100	- / -	MF	5 / 0 / Yes	-	BBC News, 2009
60	12/09/2009 Englehart, ON, Canada	36 / 0.4 / X65 / 1973 / - / 68.7 / 0.9	6.1	6.1	-	30	-	- / 150	Yes	-	Immediate / 7	C	0 / 0 / 4 families	X	TSB, 2009
61	05/11/2009 Bushland, TX, USA	24 / 0.25 / X52 / 1948 / T / 53 / 1.5	17.4	-	4.3	238	-	10.7 / -	Yes	-	3 / 50	MF	3 / 0 / 200	X	PHMSA, 2009
62	09/09/2010 San Bruno, CA, USA	30 / 0.375 / X42 / 1956 / T / 25.9 / 0.9	21.9	7.9	-	136	-	8.5 / 30.5	Yes	-	Immediate / 95	OHE	58 / 8 / 300 fam.	X	NTSB, 2011
63	30/11/2010 Natchitoches Parish, LA, USA	30 / 0.312 / X52 / 1948 / T / 46.3 / 1.5	4.6	4.6	-	17	-	1.3 / No fragments	No	None	None / 100	MF	0 / 0 / 100 families	X	PHMSA, 2011a
64	08/12/2010 E. Bernard, TX, USA	24 / 0.5 / X40 / 1947 / T / 49.6 / 1	30.5	7.6	-	182	-	3.7 / 90	No	None	None / Immediate	C	0 / 0 / Yes	X	PHMSA, 2011b
65	19/02/2011 Beardmore, ON,	36 / 0.36 / - / 1972 / - / 66.2 / 0.9	17	13	-	173	-	9 / >100	Yes	-	Immediate / 15	C	0 / 0 / 6	X	TSB, 2011

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
	Canada														
66	20/07/2011 Gillette, WY, USA	30 / 0.438 / X70 / 2010 / T / 92.4 / 0.9	27	7.5	2.7	160	1145	25 / 21	No	None	None / 85	MF	0 / 0 / 0	X	PHMSA, 2012b
67	14/11/2011 Nuevo León, Mexico	36 / - / - / - / T / - / -	20	20	5	315	4190	- / -	Yes	15	- / -	TPA	1 / 0 / 0	-	El Universal, 2011
68	16/11/2011 Glouster, OH, USA	36 / 0.344 / X60 / 1993 / T / 52.5 / -	9.1	9.1	4.6	65	800	- / -	Yes	-	- / -	MF	3 / 0 / 3 families	X	PHMSA, 2011c
69	21/11/2011 Batesville, MS, USA	24 / 0.25 / X70 / 1944 / T / 51.6 / 3.7	23.8	23.8	4.6	445	5457	1.4 / -	Yes	-	26 / 30	MF	0 / 0 / 20 families	X	PHMSA, 2013a
70	03/12/2011 Marengo C., AL, USA	36 / - / X60 / 1964 / G / 54.8 / -	24.2	16.8	4.3	320	3661	- / 61	Yes	30	Immediate / 17	-	0 / 0 / 0	X	PHMSA, 2011d
71	18/01/2012, Tresana, Italy	30 / - / - / - / - / 59 / -	20	20	7	315	5864	- / -	Yes	-	- / -	-	9 / 1 / -	-	Kraus, 2014
72	25/04/2012 Hinton, IA, USA	24 / - / - / - / - / - / -	30	10.7	9.2	252	6185	- / -	Yes	90	- / -	TPA	2 / 0 / -	-	The Gazette, 2014
73	06/06/2012 Laketon, TX, USA	26 / 0.25 / X52 / 1957 / - / 47.4 / -	18.2	5	-	72	-	15.2 / -	Yes	-	Immediate / -	-	0 / 0 / 0	X	PHMSA, 2012c
74	28/06/2012 Buick, BC, Canada	16 / 0.25 / X52 / 1960 / G / 66.6 / 0.5	17	7.6	1.1	102	300	17 / 20	Yes	-	Immediate / Previously shutdown	MF	0 / 0 / 0	X	TSB, 2013a
75	11/12/2012 Sissonville, WV, USA	20 / 0.281 / X60 / 1967 / T / 64.1 / -	22.9	10.9	4.3	195	2250	11.5 / 12.2	Yes	30	Immediate / >60	C	0 / 0 / 0	X	NTSB, 2014
76	20/08/2013 Pittsburg C, OK, USA	20 / - / - / - / - / - / -	9.1	9.1	6.1	65	1060	- / -	Yes	-	- / -	-	0 / 0 / 0	-	NewsOn6, 2013
77	08/10/2013 Harper C., OK, USA	30 / 0.344 / X52 / 1954 / T / 55.8 / 1.5	67	9.1	4.6	480	5874	67 / -	Yes	60	- / -	-	0 / 0 / Yes	X	PHMSA, 2013b
78	17/10/2013 Alberta, Canada	36 / 0.465 / - / 2008 / T / 92 / -	50	15	5	590	7854	- / 130	No	None	None / 745	MF	0 / 0 / 0	X	TSB, 2013b
79	29/11/2013 Houstonia, MO, USA	30 / 0.312 / X60 / 1962 / T / 61.6 / 1	9.5	9.5	-	70	-	- / 61	Yes	90	- / -	C	0 / 0 / 3 families	-	PHMSA, 2014b

ID	Date Place	Diameter (in) / Thickness (in) / Grade / Installation year / Type of pipeline / Pressure (bar) / Burial depth (m)	Apparent crater dimensions					Rupture length (m) / Distance to pipe fragments (m)	Ignition	Flame height (m)	Time (min) from release to ignition / to shutdown	Cause of failure	Injuries / Deaths / Evacuees	Report	Sources
			Length (m)	Width (m)	Depth (m)	Area[(a)] (m^2)	Volume[(b)] (m^3)								
80	25/01/2014 Otterburne, MB, Canada	30 / 0.37 / X52 / 1960 / - / 63.3 / -	24	12.5	3	236	1885	14.4 / 100	Yes	-	Immediate / -	MF	0 / 0 / 5 families	X	TSB, 2014
81	13/02/2014 Adair C., KY, USA	30 / 0.323 / X65 / 1965 / T / 66.3 / 9.1	-	15.2	18.3	182	-	- / 91	Yes	-	- / -	-	2 / 0 / 23 families	-	PHMSA, 2014a
82	05/04/2014 Marshall C., WV, USA	12 / - / - / - / G / - / -	3	3	-	7	-	- / -	Yes	-	- / -	-	0 / 0 / Yes	-	The Intelligencer, 2014
83	24/04/2014 France	8.6 / - / - / 1976 / - / 34 / 1	4	4	1.5	13	50	- / -	No	None	None / -	MF	- / - / -	-	ARIA, 2014
84	26/05/2014 Warren, MN, USA	24 / - / - / - / T / 56.9 / -	9.1	9.1	4.6	65	800	- / 36.6	Yes	30	- / -	-	0 / 0 / 10 families	-	DRC, 2014
85	27/06/2014 E. Godavari, AP, India	18 / - / X60 / 2001 / - / 44.1 / 5	7	7	7	39	720	0.5 / -	Yes	>25	- / -	C	40 / 18 / -	-	Mishra and Klaus-Dieter, 2015
86	23/10/2014 Ludwigshafen, Germany	16 / - / - / - / D / - / -	10	10	6	80	1260	- / -	Yes	-	- / -	TPA	11 / 1 / Yes	-	Deutsche Welle, 2014
87	14/01/2015 Brandon, MS, USA	30 / 0.375 / X52 / 1952 / T / 52.9 / -	9	8	-	57	-	- / -	Yes	>60	- / -	MF	0 / 0 / -	X	PHMSA, 2015b
88	29/01/2015 Bowling Green, MO, USA	42 / - / - / 2008 / T / - / -	6.1	6.1	-	30	-	- / -	No	None	None / -	MF	0 / 0 / 50 families	-	The People's Tribune, 2015
89	17/04/2015 Fresno, CA, USA	12 / 0.254 / X42 / 1962 / D / - / 1.1	6.1	5.6	2.2	27	157	0.8 / 6	Yes	45	Immediate / -	TPA	13 / 1 / -	X	Exponent, 2015
90	03/08/2015 Falfurrias, TX, USA	16 / 0.25 / X42 / 1947 / - / 57 / -	21.3	9.1	-	152	-	16.8 / -	No	None	None / -	C	2 / 0 / Yes	X	PHMSA, 2015c

Type of pipeline = T: Transmission, D: Distribution, G: Gathering.
Cause of failure = C: Corrosion, MF: Mechanical failure, OHE: Operational/human error, TPA: Third party activity.
[(a), (b)] These values were computed representing the shape of the crater as a semi-ellipsoid with centre at the origin of coordinates and axes coincident with the Cartesian axes.

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FIGURE CAPTIONS

Fig. 1. A cross-sectional view of a crater formed by the explosive rupture of a buried pipeline (adapted from Hansen et al., 1964 and Cooper, 1996).

Fig. 2. Domino effect sequences following a crater formation by the rupture of a buried NG pipeline.

Fig. 3. Distribution of entries according to the diameter and type of pipeline.

Fig. 4. Distribution of entries according to the depth of burial of the pipelines.

Fig. 5. Distribution of entries according to the operating pressure of the pipelines.

Fig. 6. Distribution of entries according to the length of rupture of the pipelines.

Fig. 7. Diagnostic plot $\log(C_l) \sim \log(L_r) + \log(D)$.

Fig. 8. Diagnostic plot $\log(C_d) \sim \log(L_r) + \log(B_d) + \log(D)$.

Fig. 9. Diagnostic plot $\log(C_w) \sim \log(D) + \log(B_d)$.

Fig. 10. Event tree for the release of NG from a ruptured buried pipeline.

Fig. 11. Event tree of the domino effect sequences following the formation of a crater.

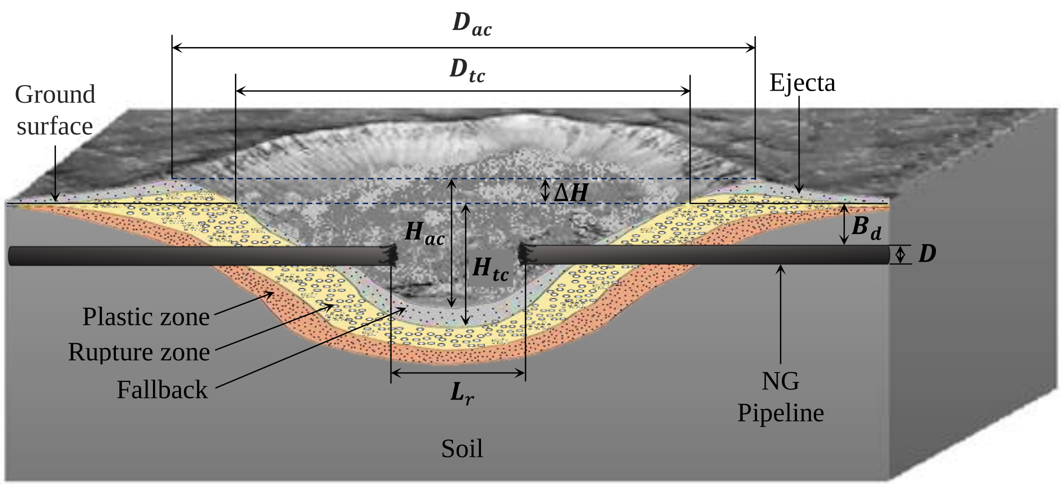
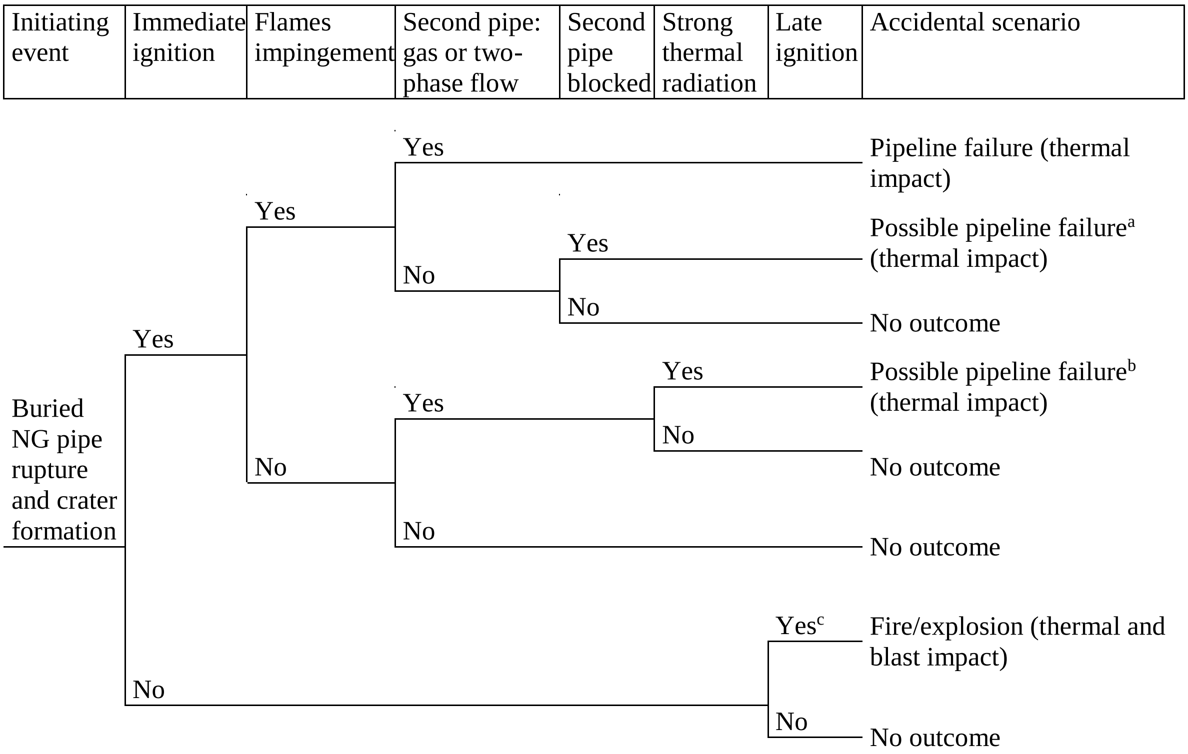


Fig. 1.



[a] Fire heating will increase pressure and could increase pipe wall temperature.
[b] Heating of pipe wall could be excessive.
[c] Depending on meteorological conditions.

Fig. 2.

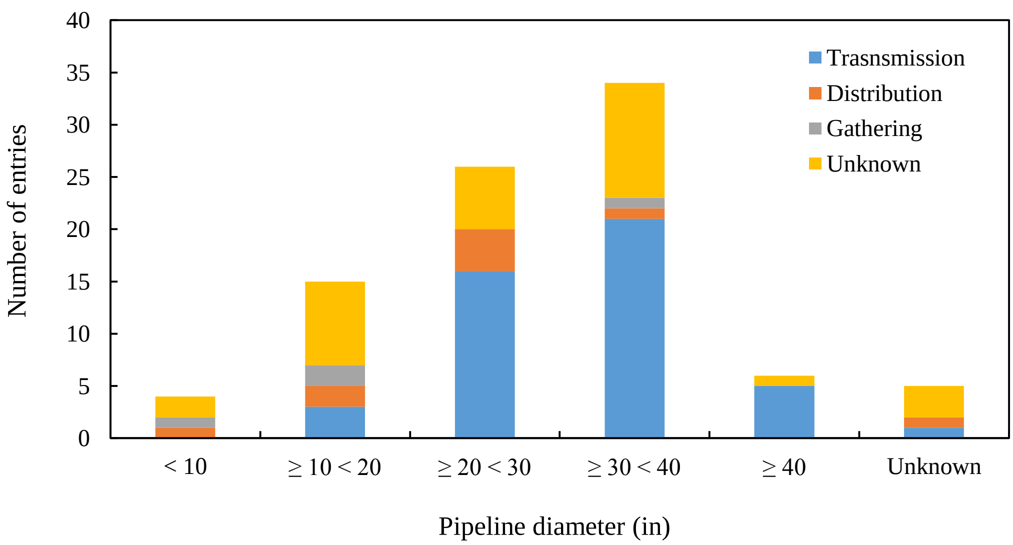


Fig. 3.

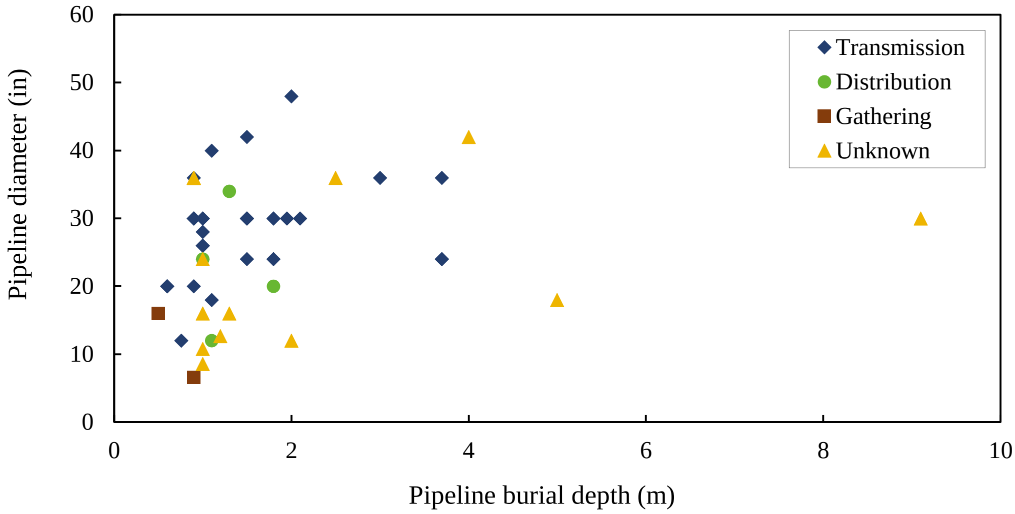


Fig. 4.

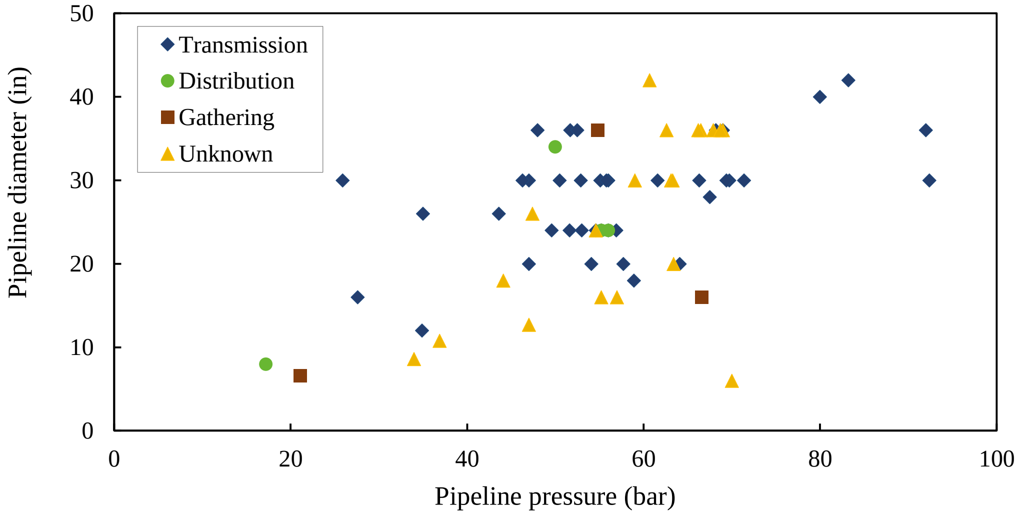


Fig. 5.

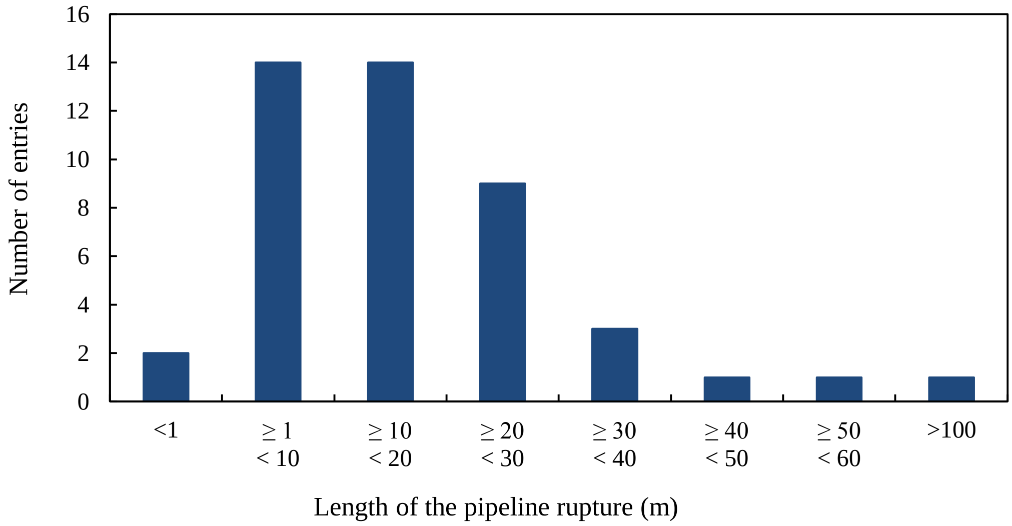


Fig. 6.

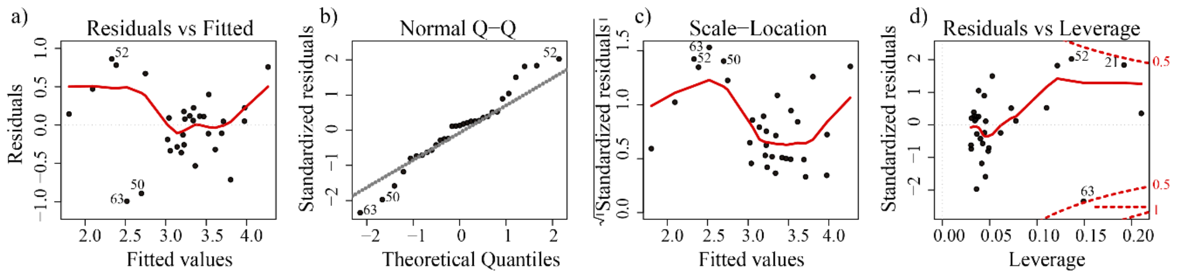


Fig. 7.

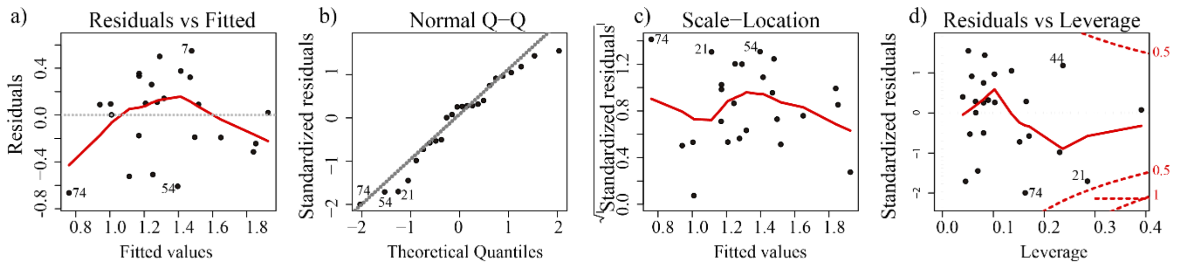


Fig. 8.

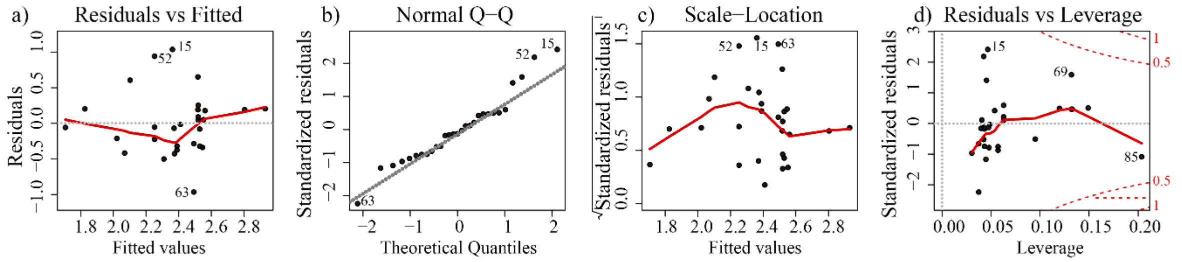
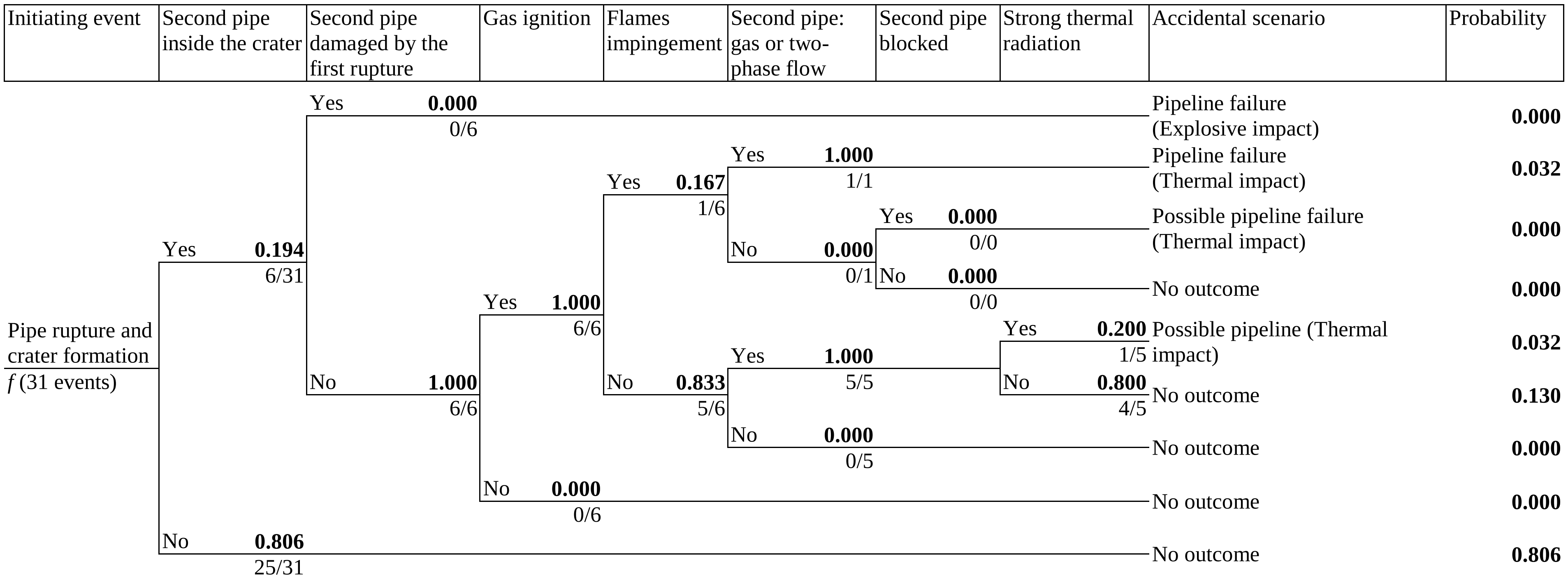


Fig. 9.

Initiating event	Immediate ignition	Delayed ignition	Flame front acceleration	Final event		Probability (*)
NG pipeline rupture *f* (90 events)	Yes **0.344** 31/90			Jet fire	22/31 = 0.710	0.244
				Fireball + Jet fire	9/31 = 0.290	0.100
	No **0.556** 50/90	Yes **0.500** 25/50	Yes **0.800** 20/25	VCE	5/20 = 0.250	0.056
				VCE + Jet fire	15/20 = 0.750	0.167
			No **0.200** 5/25	Flash fire	2/5 = 0.400	0.022
				Flash fire + Jet fire	3/5 = 0.600	0.033
		No **0.500** 25/50		Dispersion		0.278

(*) Probabilities do not total 1 since the type of ignition is unknown in 9 entries.

Fig. 10.



Initiating event
Second pipe inside the crater
Second pipe damaged by the first rupture
Gas ignition
Flames impingement
Second pipe: gas or two-phase flow
Second pipe blocked
Strong thermal radiation
Accidental scenario
Probability
Pipe rupture and crater formation
f (31 events)
Yes 0.194 6/31
No 0.806 25/31
Yes 0.000 0/6
No 1.000 6/6
Yes 1.000 6/6
No 0.000 0/6
Yes 0.167 1/6
No 0.833 5/6
Yes 1.000 1/1
No 0.000 0/1
Yes 0.000 0/0
No 0.000 0/0
Yes 1.000 5/5
No 0.000 0/5
Yes 0.200 1/5
No 0.800 4/5
Pipeline failure (Explosive impact) 0.000
Pipeline failure (Thermal impact) 0.032
Possible pipeline failure (Thermal impact) 0.000
No outcome 0.000
Possible pipeline (Thermal impact) 0.032
No outcome 0.130
No outcome 0.000
No outcome 0.000
No outcome 0.806

Fig. 11.

HIGHLIGHTS

- The catastrophic rupture of a buried pipeline can create a crater.
- The formation of a crater is a relevant event due to its destructive potential.
- In parallel pipelines, the formation of a crater can lead to a domino effect.
- Influence of the pipe parameters on the resulting crater has been evaluated.
- Results obtained can be used to support distances between parallel pipelines.