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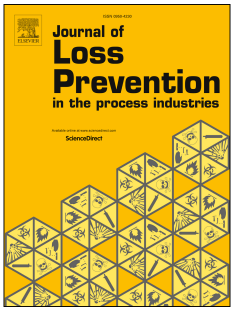

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Underground parallel pipelines domino effect: an analysis based on pipeline crater models and historical accidents

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Abstract

This paper focuses on the analysis of the possibility of domino effect in underground parallel pipelines relying on historical accident data and pipeline crater models. An underground pipeline can be considered as safe following an accident with an adjacent gas or liquefied pipeline when it remains outside the ground crater generated. In order to prevent the domino effect in these cases, the design of parallel pipelines has to consider adequate pipeline separations based on the crater width, which is one of the widely used methods in engineering applications. The objective of this work is the analysis of underground petroleum product pipelines ruptures with the formation of a ground crater as well as the evaluation of possible domino effects in these cases. A detailed literature survey has been carried out to review existing crater models along with a historical analysis of past accidents. A FORTRAN code has been implemented to assess the performance of the Gasunie, the Batelle and the Advantica crater models. In addition to this, a novel Accident-Based crater model has been presented, which allows the prediction of the crater width as a function of the relevant design pipeline parameters as well as the soil density. Modifications have also been made to the Batelle and Accident-Based models in order to overcome the underestimation of the crater width. The calculated crater widths have been compared with real accident data and the performance evaluation showed that the proposed Accident-Based model has a better performance compared to other models studied in this work. The analysis of forty-eight past accidents indicated a major potential of underground parallel pipelines domino effect which is proven by two real cases taken from the literature. Relying on the investigated accidents, the crater width was smaller than or equal to 20 meters in most cases indicating that the definition of underground pipeline separations at around 10 meters would be sufficient to ensure a small probability of the domino effect.

Keywords: Underground pipelines, Domino effect, Risk assessment, Past accidents

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Nomenclature

Abbreviations

CONCAWE	Conservation of Clean Air and Water in Europe
DOT	United States Department of Transportation
EGIG	European Gas Pipeline Incident Data Group
HSE	Health and Safety Executive
LNG	Liquified Natural Gas
LPG	Liquified Petroleum Gas
NA	Not available
NTSB	United States National Transportation Safety Board
PHMSA	Pipeline Hazardous Material Safety Administration
TSB	Transportation Safety Board of Canada
UKOPA	United Kingdom Onshore Pipeline Operator's Association
USDA	United States Department of Agriculture
WSS	Web Soil Survey

Greek Symbols

α_{C1}	Crater angle wall at ground level (deg)
α_{C2}	Crater angle wall at half of the crater depth (deg)
γ	Specific heat ratio of the gas ($-$)
ρ	Density of the gas (kg/m^3)
ρ_{soil}	Density of the soil (kg/m^3)

Roman Symbols

a	Length of the semi-minor axis of the elliptically shaped crater (m)
A_{dyn}	Work required to disturb a unit of mass of soil (J)
b	Length of the semi-major axis of the elliptically shaped crater (m)
c	Speed of sound (m/s)
CW	Crater width (m)
D	Crater depth (m)
D_c	Depth of cover (m)
D_p	Pipeline diameter (m)
m_i	Correlation constant (m)
n_i	Correlation constant ($m/inch$)
NPS	Nominal Pipe Size (in)
P	Pipeline operating pressure (bar)
Q_w	Energy per unit mass of the explosion (J/kg)
$R(w)$	Function of the soil parameter
u_x	Outburst speed of the explosive gases (m/s)
u_{kr}	Critical velocity (m/s)
w	Soil parameter ($-$)

1. Introduction

The evolving demand for oil and natural gas supply along with the efficiency of distributing them by using pipelines over long distances generates need for construction of a number of pipelines.

On the other hand, the need of easements or servitudes to provide the passage of pipelines launches a challenge to pipeline operators to design pipelines to minimize land conflicts and environmental impacts. At the same time, it is necessary to assure the safety of population. The solution to these issues often involves the construction of parallel pipelines along new or existing right-of-ways (rows).

The underground parallel pipelines escalation or domino effect could occur when two or more pipelines run adjacent to a gas or liquefied pipeline. When it happens, the consequences of the final event are notably greater than the consequences associated with the primary event [1]. Therefore, neglecting the evaluation of the domino effect in the risk assessment of underground parallel pipelines can give rise to a risk underestimation [2, 3].

The rupture of an underground gas or liquefied product pipeline occurs with the formation of a ground crater by the source jet [4, 5, 6]. When the released gas ignites, the fire will develop inside the crater [7]. If an adjacent pipeline is present in the row and outside the crater formed, it will remain safe as it is protected by the surrounding soil. However, if the adjacent pipeline is inside the crater, it will be subject to the pressure exerted by the gas released on the soil and the thermal load generated by the fire. In this instance, there is the possibility of the domino effect [8]. According to [5], among twelve incidents involving a rupture of underground pipelines, one incident was reported in which domino effect was believed to have occurred.

In this paper, among 17 accidents involving underground parallel pipelines, two cases of domino effect have been identified. To prevent underground parallel pipelines domino effect, it is necessary to define minimum separations between two or more pipelines adjacent to gas pipelines, or to implement mitigating measures ensuring that they may be arranged and operated safely [5, 9, 10].

A schematic drawing of an arrangement of three parallel pipelines is shown in Figure 1 as can be designed in a row, and Figure 2 illustrates an example where the failure of pipeline 2 generates a crater.

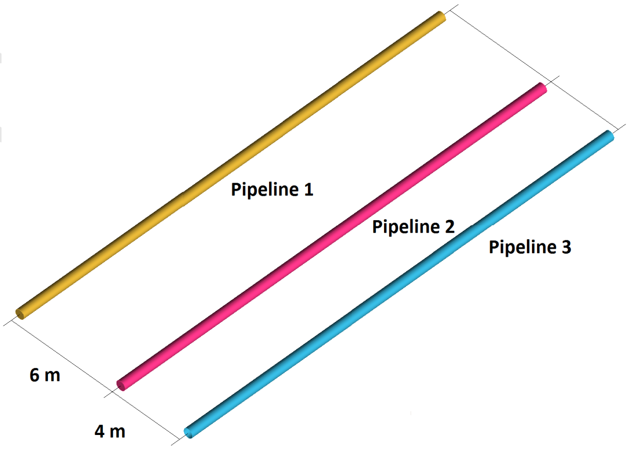


Figure 1: Schematic drawing of the pipeline arrangement in a row.

In Figure 2, pipeline 1 can be considered as safe, because it is outside the crater. However, pipeline 3 would be subject to a ground pressure load during the crater formation and a thermal load caused by the jet fire in case of ignition. Therefore, the safety of pipeline 3 will depend on whether it can withstand these loads without losing its integrity [5, 7].

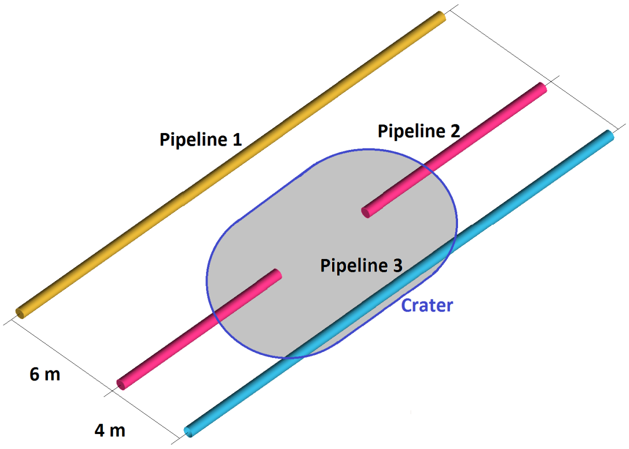


Figure 2: Crater schematic drawing with parallel pipelines.

An example of an accident involving underground parallel pipelines without domino effect is shown in Figure 3. This accident occurred in Ghislenghien, Belgium, in 2004. The ruptured pipeline transported natural gas at a pressure of 80 *bar* with the diameter of 39 *inch*. At the accident site, a parallel pipeline with the diameter of 35 *inch* was operating at a distance of 7 *m* [11] (see the crater dimensions in Figure 3). It can also be seen in Figure 3 that the adjacent pipeline was damaged, but remained safe after the accident. It is important to note that the most part of the adjacent pipeline is outside the crater formed and it may have been protected from the crater fire.

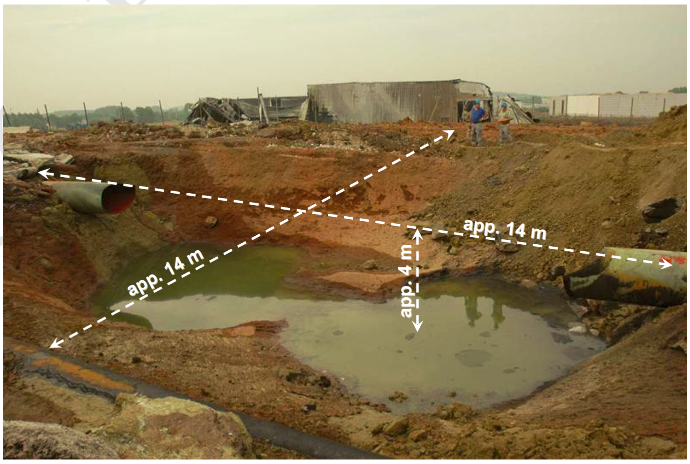


Figure 3: Parallel pipelines in an accident without domino effect [11].

In contrast to the Belgium accident, Figure 4 shows an accident involving underground parallel pipelines with domino effect, which occurred near Buick, British Columbia, in Canada, in 2012. The "Nig Creek" pipeline ruptured first transporting natural gas at a pressure of 66.54 *bar* with the diameter of 16 *inch*. At the accident site, the "Bonavista" pipeline with the diameter of 6.625 *inch* at operating pressure of 8.69 *bar* ruptured approximately 25 minutes later [12]. In this instance, a section of the "Bonavista" pipeline is entirely inside the crater. According to the incident investigation, its rupture exhibited a thin-lipped "fish mouth" feature, which is a characteristic of a pipeline failure due to overheating [12], thus it can be concluded that the domino effect had occurred by thermal load.

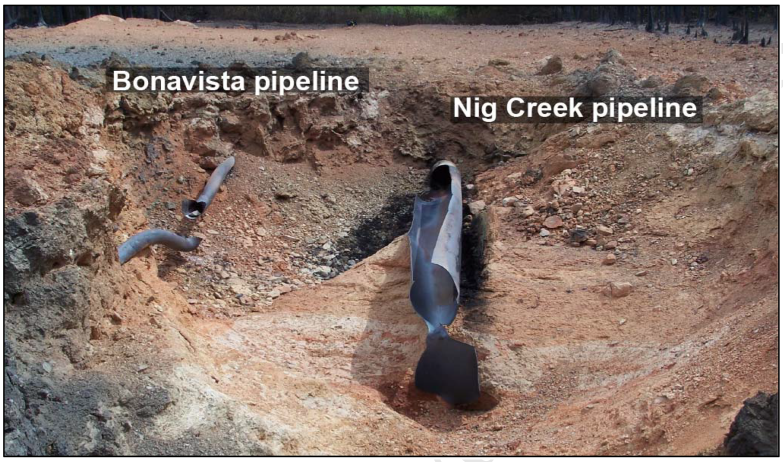


Figure 4: Parallel pipelines in an accident with domino effect [12].

The design of pipeline separations relying on the crater width is the simplest way of assuring that a parallel pipeline in a row will remain safe following an accident with a gas pipeline. In this respect, pipeline companies have developed different models to predict the crater dimensions generated after an accident. When underground pipeline separations are defined by using crater models, it is very important that the crater model could appropriately represent the crater dimensions. Owing to this fact, the objective of this study is to investigate the possibility of underground parallel pipelines domino effect relying on real accidents.

2. Pipeline Crater Models

The objective of this work is the analysis of petroleum product pipelines ruptures with the formation of a ground crater as well as the evaluation of possibile domino effects in these cases. Four main models have been identified to predict the dimensions of a crater generated by a pipeline failure such as (i) Gasunie, (ii) Batelle, (iii) NEN 3651 equations, and (iv) Advantica model. The discussion on the NEN 3651 model has been excluded from this Section, because the assumptions used in its development were not available in the literature.

2.1. Gasunie Model

The Gasunie model was developed by the Delft Hydraulics Laboratory and sponsored by a transmission pipeline company in The Netherlands. It relies on the assumptions that the soil can be considered as a homogeneous medium, the two end pipes are separated after the rupture, and the crater formation occurs in two stages. The first stage consists of the displacement of the soil near the pipeline to form the crater. In the second stage, the axial length of the crater is increased by the erosion of the soil caused by the gas flow [9].

The cross-sectional shape of the crater is considered elliptical in this model. The main characteristics are the crater width, CW, the crater depth, D, the crater angle wall at ground level, α_{C1}, and the crater angle wall at half of the crater depth, α_{C2} as shown in Figure 5 [9].

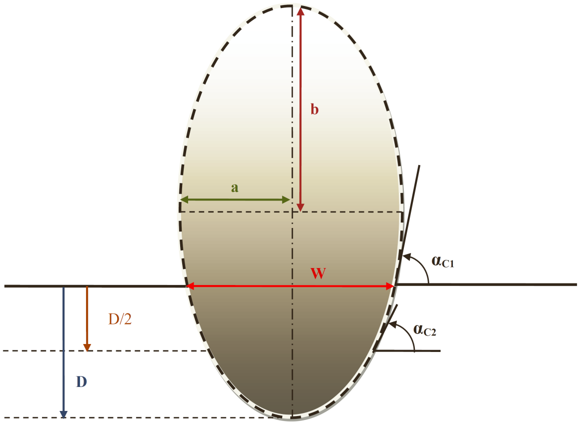


Figure 5: Representation of the crater cross-section [9].

To compute the crater dimensions by using the Gasunie model, the input parameters are required as a) pipeline diameter, b) depth of cover, and c) qualitative description of the soil. The crater depth D is considered independent of the soil type for ruptures on the top of the pipeline and determined as [9]

$$D = D_p + D_c, \tag{1}$$

where D_p is the diameter of the pipeline and D_c is the depth of cover. For guillotine ruptures, the soil type and the moisture content influences the crater depth D, which can also be determined as [9]

$$D = \begin{cases} 4.3D_p + D_c, & if\ w \leq 0.6, \\ \frac{R(w)D_p}{0.3} + D_c, & if\ 0.6 < w < 2, \\ 2.2D_p + D_c, & if\ w \geq 2, \end{cases} \tag{2}$$

where $R(w)$ is a function of the soil parameter, w, and is defined by

$$R(w) = 0.28 + 0.62\,(5 - w) - 0.07\left(25 - w^2\right). \tag{3}$$

The crater angles α_{C1} and α_{C2} are also a function of the soil parameter as [9]

$$\alpha_{C1} = tan^{-1}\,(w + 1)\,, \tag{4}$$

$$\alpha_{C2} = tan^{-1}\left[\left(\frac{2.8 + 0.5w}{10}\right)(w + 1)\right], \tag{5}$$

and values of crater angles for different soil types are shown in Table 1 [9].

Table 1: Parameter, w, and crater angles as a function of the soil classification [9].

Type of soil	w	$\alpha_{C1}(deg)$	$\alpha_{C2}(deg)$
Very dry sand	0.75	60	29
Sand or dry mixed soil	1.10	65	35
Mixed soil or gravel	1.75	70	45
Humid mixed soil, clay or rock	2.70	75	57
Heavy clay	5.00	80	73

The crater width is determined by [9]

$$CW = 2a\sqrt{1 - \frac{(b - D)^2}{b^2}}, \tag{6}$$

where a and b are determined as

$$tan\,\alpha_{C1} = \frac{b}{a}\sqrt{\left(\frac{b}{b - D}\right)^2 - 1}, \tag{7}$$

and

$$tan\,\alpha_{C2} = \frac{b}{a}\sqrt{\left(\frac{b}{b - 0.5D}\right)^2 - 1}. \tag{8}$$

The Gasunie model provides simple empirical correlations in order to model the crater dimensions generated by a pipeline rupture considering characteristics of the soil and the pipeline. However, it does not take into account the pipeline operating pressure when the crater is modeled. This limitation could lead to an underestimation of the crater width of the pipelines when operating at high pressures and could overestimate it when operating at low pressures [13]. Furthermore, the Gasunie model lacks correlations for computing the crater length, although it is assumed that the crater length is increased which is caused by the gas flow. Another shortcoming of this model lies on the fact that the crater angles are computed by using only the soil type excluding the pressure and the diameter of the pipeline. It is also difficult to correlate the actual soil data with the soil types which have been presented in Table 1.

2.2. Batelle Model

The Batelle model was originally developed relying on studies conducted by the Batelle Institute [9] representing a work to further improve the Gasunie model described in Section 2.1. For estimating the crater width, correlations have been derived by considering that the physics governing the crater formation in a pipeline rupture has similar characteristics to the crater formation by chemical explosions.

This model considers that the crater has cross-sections in two-dimensions and the cross-section perpendicular to the axis of the ruptured pipeline is sufficient to determine whether the adjacent pipeline is uncovered during the crater formation. In addition to these features, it is assumed that the crater depth correlations valid for the Gasunie model are also used for this model.

For modeling crater formation by an explosion of an infinitely long buried explosive when the medium is an incompressible fluid, the outburst speed of the explosive gases can be calculated as [9]

$$u_x = \sqrt{\frac{2\rho Q_w}{3\rho_{soil}}}, \tag{9}$$

where ρ and ρ_{soil} are the gas and soil densities, respectively, and Q_w is the energy per unit mass of the explosion given by

$$Q_w = \frac{c^2}{2\left(\gamma^2 - 1\right)}, \tag{10}$$

where γ is the specific heat ratio of the gas, c is the speed of sound, and the crater width is calculated by

$$CW = 2\sqrt{\frac{D_p\left(D_c + \frac{D_p}{2}\right)}{u_{kr}}u_x - \left(D_c + \frac{D_p}{2}\right)^2}. \tag{11}$$

The critical velocity u_{kr} can displace the soil such as

$$u_{kr} = \sqrt{\frac{2A^{dyn}}{\rho_{soil}}}, \tag{12}$$

where A_{dyn} is the work required to disturb a unit volume of mass of soil and determined empirically. In the absence of this information, the critical velocity can be taken as an average value of $2.54\,m/s$ [9].

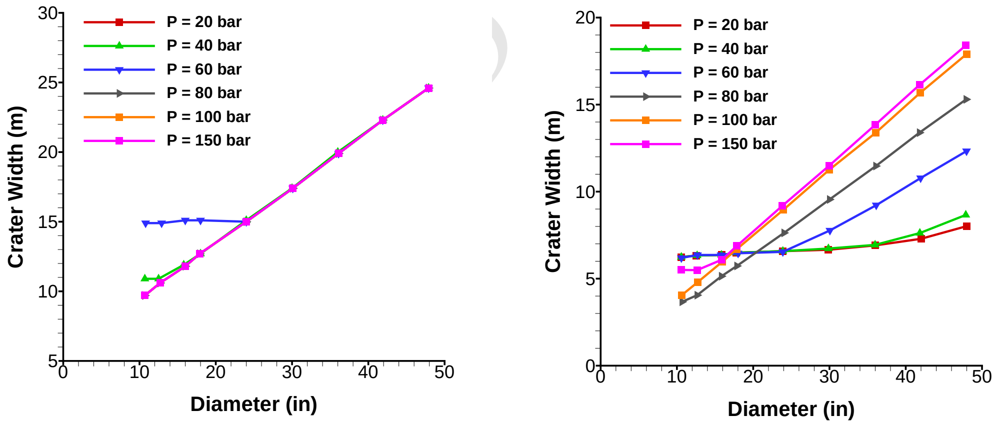
As a matter of fact, the Batelle model represents a significant improvement to the Gasunie model introducing variables in the modeling of the crater width such as the specific heat ratio of the gas, soil density and the pipeline operating pressure. However, the crater depth is calculated by using a qualitative soil characteristic whereas the crater width calculations make use of the soil density which is a quantitative characteristic of the soil. These considerations make this model not very practical, because there is no simple way of correlating these two features. This model still needs correlations for the crater length and presents the same shortcomings inherited from the Gasunie model when the crater depth is modeled.

2.3. Advantica Model

The Advantica model was developed within a collaborative project to provide guidance on escalation involving buried adjacent pipelines. This investigation was conducted by a number of gas transmission pipelines with the technical coordination of GL Noble Denton (formerly Advantica) [5]. 130

The Advantica model developers [5] presented results of twelve experiments involving the release of natural gas at pressure levels between 20 and 150 *bar* from holes of diameters 25 or 80 *mm* conducted at GL's Spadeadam Test Site [5]. The size and shape of the ground craters were measured after each experiment and effect distances between adjacent pipelines where escalation will less likely occur were defined. 135

The results of the crater width were not presented by the authors of the Advantica model [5], however they emphasized that the effect distances were measured from the centerline of the first pipeline to the nearest point on the wall of the other pipeline. It is inferred from this information that the maximum value of the crater width has to be twice as much as the effect distance. In this way, the maximum crater width could be calculated by extracting data from the figures presented in reference [5]. The crater width based on the pipeline pressure and diameter for sandy and clay soils are shown in Figure 6. The maximum crater width for clay, mixed and sandy soils at pressure levels up to 80 *bar* is shown in Figure 7. 140



(a) Sandy soil

(b) Clay soil

Figure 6: Crater width based on the pipeline pressure and diameter.

145 Figures 6 and 7 exhibit that the crater width varies linearly with the diameter of the pipeline. For a sandy soil, the pipeline pressure has a minor impact except for pressure levels of 40 and 60 *bar* when the crater width for punctures at smaller diameters are greater than the crater width for ruptures. Despite of this fact, for a clay soil, the pressure has a major impact on the crater width when it increases with the increment of the pipeline operating pressure. For the same conditions of pressure and pipeline diameter, a lower crater width is obtained for a clay soil compared to the 150

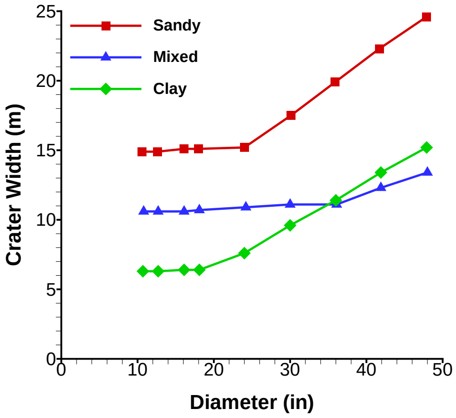


Figure 7: Maximum crater width for clay, mixed and sandy soil at pressure levels up to 80 *bar*.

results of a sandy soil (see Figure 6). It also means that during the design of underground pipelines parallel to gas pipelines the separation distances in sandy soils are expected to be higher than in clay soils.

3. Methodology

3.1. Pipeline accident characterization

The study on previous accidents is the usual way to learn about their circumstances, causes and consequences [14]. By reviewing the sequence of events that occurred during an accident it is possible to provide criteria to develop effective mitigating measures to prevent a similar accident or minimize the damage it would be able to cause. Within this context, this section focuses on the review of past accidents involving pipelines where the crater dimensions were recorded. In order to gain information from as different sources as much as possible, a literature survey has been carried out including books, reports, articles, pipeline accident databases and pipeline design standards. It has been found that the most important literature sources on pipeline craters come from the study of pipeline accidents published by international regulatory agencies such as the United States National Transportation Safety Board (NTSB), the Pipeline and Hazardous Material Safety Administration (PHMSA), and the Transportation Safety Board (TSB) of Canada. The "Lee's Loss Prevention in The Process Industries" book [15], two reports by the United Kingdom Health and Safety Executive (HSE) [4, 16], and a report by the BAM Federal Institute for Materials Research and Testing [17] represent a scientific contribution on this subject. A wide range of data are accessible on pipeline incidents in EGIG [18], UKOPA [19], and CONCAWE [20] databases, however there is a lack of available information on crater formed after these accidents.

Extensive lists of accidents are accessible through internet sources where essential characteristics of the pipeline craters are not described. These lists can be considered as additional sources to track other references, although they often do not contain reliable data.

Most of the reports include information on location, date and time of the accident, pipeline data, and crater dimensions. On the other hand, only a few reports provide data on the soil type where the accident occurred.

In order to gain reliable data on soil types for evaluating the performance of the crater models discussed in the previous section, the databases provided by soil agencies have been analyzed. The methodology consists of the accurate identification of the accident location and the analysis of soil characteristics to classify the soil type based on the classes established by the respective agencies.

The site locations of accidents that occurred in the United States have been accurately identified with the aid of the National Pipeline Mapping System (NPMS) Public Map Viewer [21] whereas the soil data have been characterized with the aid of the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture (USDA), which provides soil data through the Web Soil Survey (WSS) [22]. This has not been possible for accidents that occurred in other countries due to the lack of similar tools.

As an example of this methodology, a pipeline accident site reported in [23] has been shown in Figure 8 and the location of this accident site on the pipeline route and soil map can be seen in Figure 9.

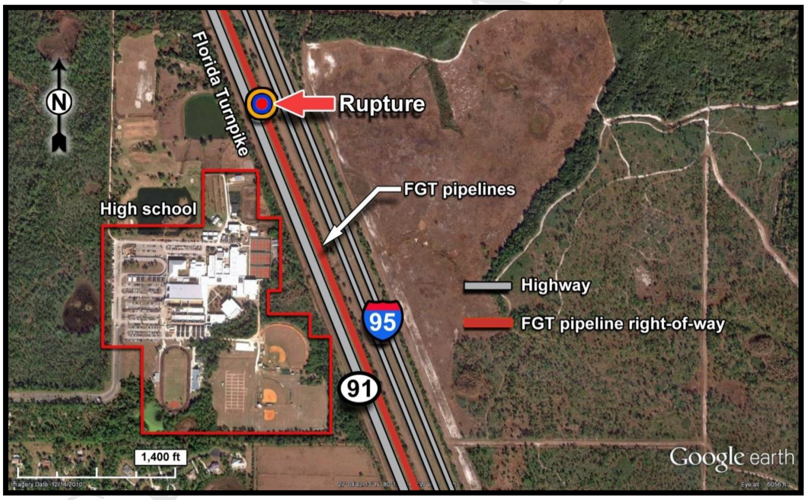


Figure 8: Indication of a pipeline accident site [23].

(a) Route map [21] (b) Soil map [22]

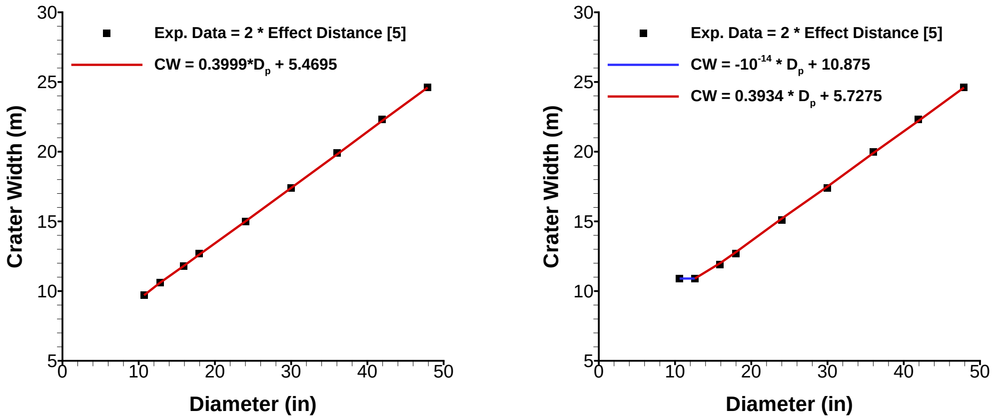
Figure 9: Location of the accident pipeline site on the route and soil map.

3.2. Correlations for the Advantica model

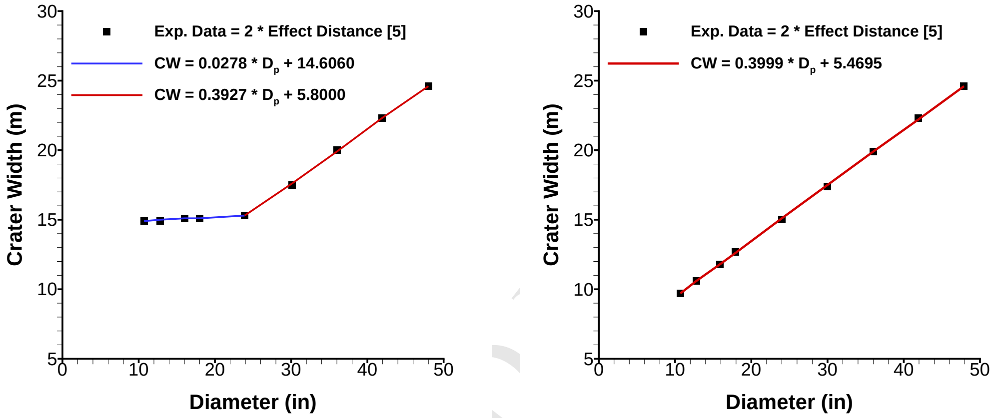
This subsection presents crater width correlations for the Advantica model relying on different soil types, pipeline diameters and operating pressures. Modifications have been made in conjunction with the estimation of the crater width, which is not directly given by the Advantica model. 195 Therefore, to estimate the correlations a) the values of the effect distance points have been extracted and doubled based on the data published in [5], and b) correlations have been obtained by applying the method of linear regression as

$$CW_i = n_i \cdot D_p + m_i, \tag{13}$$

where n_i and m_i are empirical correlation constants related to different soil types and pipeline operating pressure levels. Figures 10 to 12 show that the method of linear regression estimates 200 accurately these empirical constants against the experimental data of doubled effect distances.

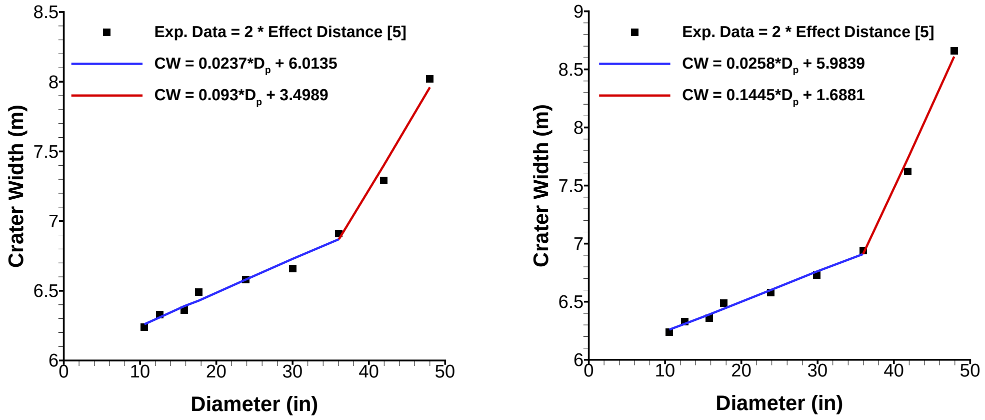


(a) P = 20 bar (b) P = 40 bar

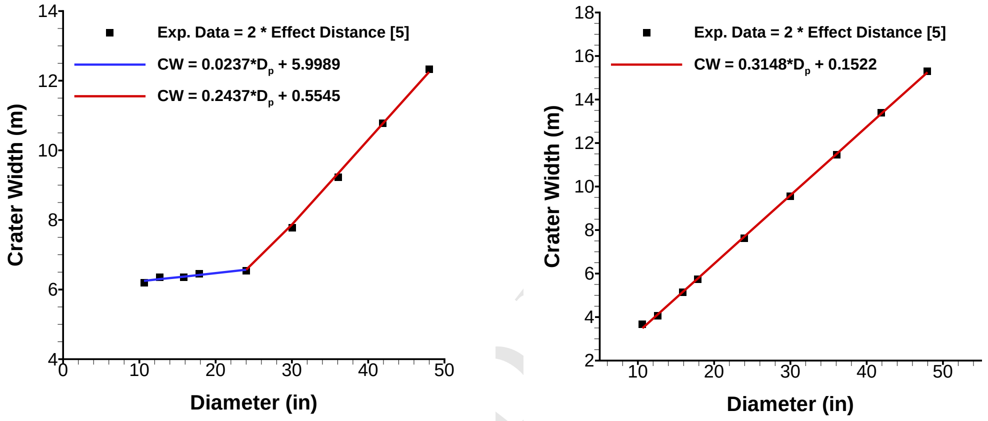


(c) P = 60 bar (d) P = 80-150 bar

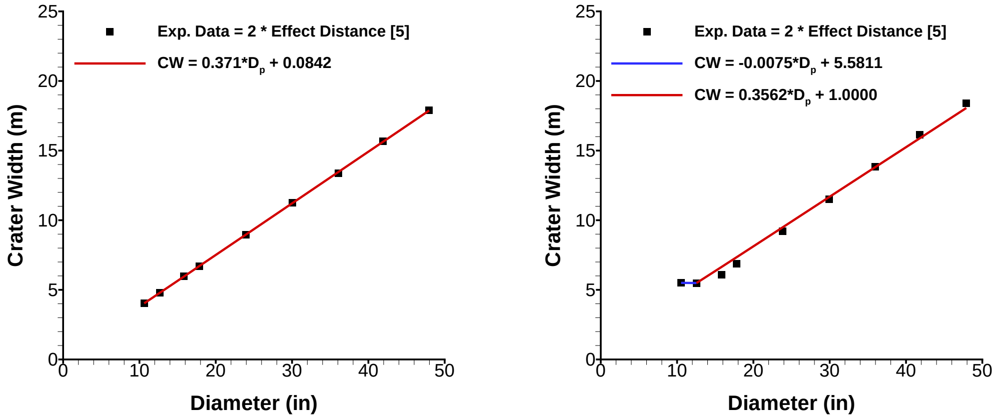
Figure 10: Correlations for the maximum crater width for sandy soil.



(a) P = 20 bar (b) P = 40 bar



(c) P = 60 bar (d) P = 80 bar



(e) P = 100 bar (f) P = 150bar

Figure 11: Correlations for the maximum crater width for clay soil.

For mixed soil, there is only one curve presented, because data were available at pressure levels up to 80 *bar* (see Figure 12).

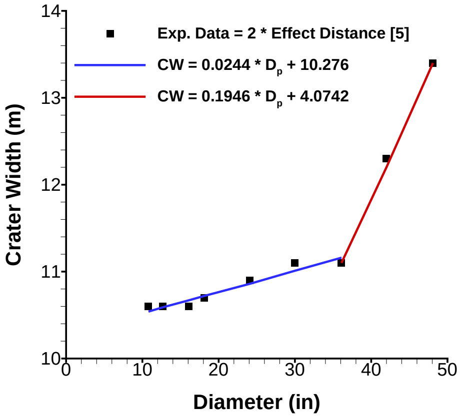


Figure 12: Correlations for the maximum crater width for mixed soil.

The experimental data were available for the effect distances in [5], and the values of the empirical constants in Eq. (13) for the crater width were not published relying on the Advantica model (see Table 2, and Figures 10 to 12).

Table 2: Correlations for the Advantica Model at different pipeline operating pressures.

Soil Type	Pressure (bar)	Diameter range (in)	Correlation
Sandy soil	20	*any*	$CW = 0.3999D_p + 5.4695$
	40	≤ 12.8	$CW = -10^{-14}D_p + 10.875$
		> 12.8	$CW = 0.3934D_p + 5.7275$
	60	≤ 24.0	$CW = 0.0278D_p + 14.6060$
		> 24.0	$CW = 0.3927D_p + 5.8000$
	80 – 150	*any*	$CW = 0.3999D_p + 5.4695$
Clay soil	20	≤ 36.1	$CW = 0.0237D_p + 6.0135$
		> 36.1	$CW = 0.093D_p + 3.4989$
	40	≤ 36.0	$CW = 0.0258D_p + 5.9839$
		> 36.0	$CW = 0.1445D_p + 1.6881$
	60	≤ 24.0	$CW = 0.0237D_p + 5.9989$
		> 24.0	$CW = 0.2437D_p + 0.5545$
	80	*any*	$CW = 0.3148D_p + 0.1522$
	100	*any*	$CW = 0.3710D_p + 0.0842$
	150	≤ 12.6	$CW = -0.0075D_p + 5.5811$
		> 12.6	$CW = 0.3562D_p + 1.0000$
Mixed soil	≤ 80.0	≤ 36.1	$CW = 0.0244D_p + 10.276$
		> 36.1	$CW = 0.1946D_p + 4.0742$

3.3. An in-house FORTRAN code to calculate pipeline crater dimensions

The correlations of each model have been implemented in an in-house FORTRAN code called as “PIPELINE CRATER MODELING” (see the flowchart in Figure 13).

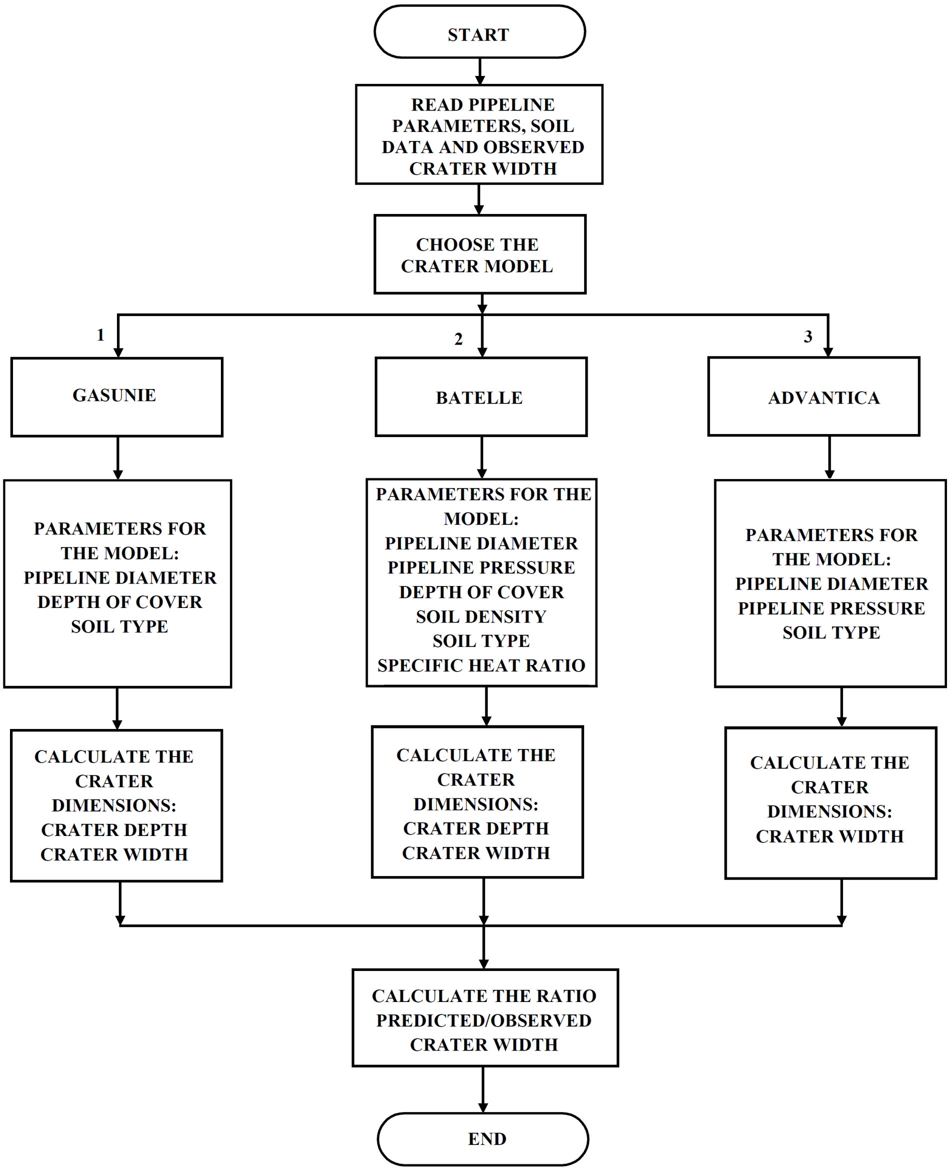


Figure 13: Flowchart of crater modeling FORTRAN program.

The program reads the pipeline and soil parameters such as diameter, depth of cover and
210 operating pressure, soil density, type and critical velocity, respectively. After the model selection, a subroutine is called to calculate the crater dimensions and all technical parameters are taken into account by using the model correlations.

The soil type is an input parameter for the crater width. The Gasunie, Batelle and Advantica models treat the soil characteristics and classification qualitatively whereas the USDA classification is estimated quantitatively based on the sand, silt and clay contents. In addition to this, the number of the USDA soil classes are different compared to the crater models. Therefore, it was necessary to establish a relationship between the soil classifications of the USDA and of the crater models (see Table 3). In order to determine these relationships, the authors refer to a personal communication with Professor Helena Polivanov, soil geologist at the Federal University of Rio de Janeiro.

Table 3: Relationship between the USDA soil Classes and Gasunie, Batelle and Advantica Soil Types.

USDA soil classes	Gasunie/Batelle	Advantica
Sand	Very dry sand	Sand
Loamy sand, sandy loam	Sand or dry mixed soil	Mixed
Loam, silt loam, silt, clay loam, sandy clay	Mixed soil or gravel	Mixed
Sandy clay loam, silty clay loam, silty clay	Humid mixed soil, clay or rock	Mixed
Clay	Heavy clay	Clay

Case studies have been carried out to predict the dimensions of the crater formed by a pipeline rupture taking into account the characteristics of the pipeline and the soil. The main parameters considered in the case studies have been shown in Table 4.

Table 4: Selected set of accidents to evaluate the crater models.

Accident		Transported material		Pipeline data			Soil characteristics	
Case	ID	Product	γ	Diameter (in)	Pressure (bar)	Depth of cover (m)	Soil class	Soil density (kg/m^3)
1	1	Natural gas	1.270	24.0	54.6	1.0	Sandy loam	1360
2	2	Propane	1.127	8.6	66.2	1.5	Silt loam	1480
3	3	Ammonia	1.310	8.6	82.7	1.0	Silt loam	1340
4	4	LNG	1.108	10.8	36.9	1.0	Clay	1270
5	9	LPG	1.270	8.6	100.0	0.9	Clay	1360
6	13	Natural gas	1.270	20.0	57.7	0.9	Silty clay loam	1350
7	14	Natural gas	1.270	30.0	71.4	0.9	Sandy loam	1480
8	16	Natural gas	1.270	30.0	69.7	1.8	Silt loam	1470
9	20	Natural gas	1.270	30.0	69.4	1.8	Rocky	1390
10	28	Natural gas	1.270	36.0	68.2	3.7	Loam	1420
11	29	Natural gas	1.270	36.0	69.0	0.9	Gravel	NA
12	30	Natural gas	1.270	42.0	60.7	4.0	Mixed	NA
13	31	Natural gas	1.270	34.0	50.0	1.3	Clay	NA
14	36	Natural gas	1.270	20.0	46.9	0.6	Rocky	1390
15	39	Natural gas	1.270	24.0	54.8	1.8	Sand	1400
16	41	Natural gas	1.270	18.0	58.9	1.1	Silt loam	1540
17	45	Natural gas	1.270	24.0	51.6	3.7	Rocky	1360

It is important to mention that a subset of accidents from Table A1 in the Appendix has been used, because all the necessary parameters were available only for seventeen cases. The calculated results have been compared with real accident values to evaluate the performance of the implemented crater models.

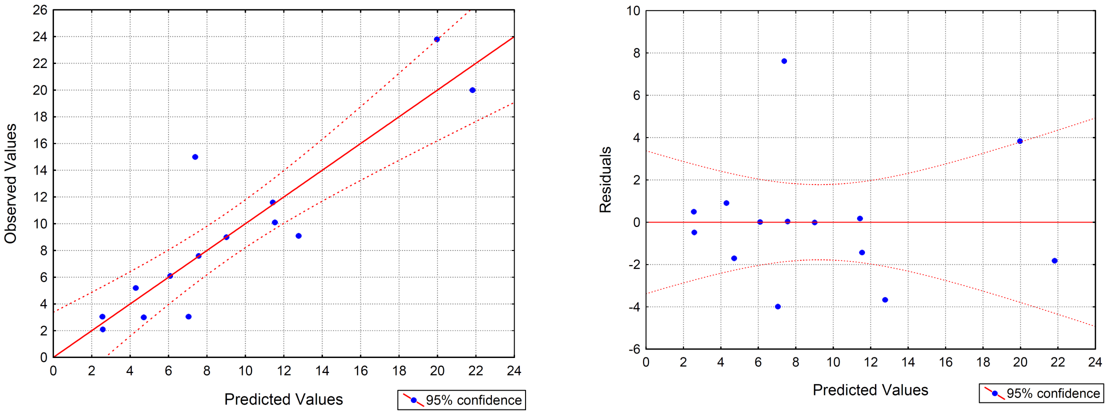
3.4. A model based on accidents

In this section, we present a novel crater model development based on data from real accidents. All crater models presented in previous sections were based on experimental investigation of the crater dimensions with different characteristics of the pipeline and soil. A mathematical approach has been developed which allows the prediction of the crater width as a function of the technically relevant pipeline parameters such as diameter, depth of cover, operating pressure and the specific heat ratio of the gas transported as well as the soil density.

The determination of functional dependence between these parameters and the crater width has been made by employing the multiple linear regression tool from STATISTICA software package. Relying on the data presented in Table 4, a polynomial correlation between the crater width and the real accident data can be predicted as

$$CW = 33.646 + 0.315D_p - 0.056P + 3.995D_c - 8.304\gamma - 0.017\rho_{soil}, \tag{14}$$

and the statistical evaluation of the model is illustrated in Figure 14, which shows scatterplots of predicted versus observed and predicted versus residuals values. It is possible to verify that the crater width correlates well with the real accident data, because most of the observed values are within or near the 95% confidence limit and the residuals fluctuate randomly around zero.



(a) Predicted versus observed.

(b) Predicted versus residuals.

Figure 14: Accident-Based crater model scatterplots.

4. Results and Discussion

4.1. Real accident analysis

In this Section forty-eight real accidents have been studied related to pipeline failures with recorded crater sizes from 1965 to 2012. Among these identified cases, forty-three accidents involved gas pipelines (natural gas and propane), three cases occurred related to liquefied products pipelines (ammonia, LNG and LPG), one case involved a liquid pipeline (naphtha), and another case was a pipeline accident with a mixture gas (natural gas + liquids + CO_2). A detailed list of the main characteristics of these events can be found in the Appendix.

Most accidents reported in the literature occurred in the Unites States (31 cases) and in Canada (12 cases). The low number of occurrences in other countries might be due to the lack of detailed incident investigation reports available to the public. For example, it has been found that a total of 1,309 incidents was recorded in the EGIG [18] database from 1970 to 2013, however no detailed incident investigation report for these accidents has been found.

Out of the accidents studied, seventeen cases involved underground parallel pipelines as presented in Table 5. These parallel pipelines accidents have also been highlighted in the Appendix.

Table 5: Accidents involving underground parallel pipelines.

ID	Pipeline	NPS(in)	Product	Condition after the accident
5	Line C	42.0	NA	Not exposed, safe
	Line A	30.0	NA	Not exposed, safe
	Line B	30.0	Natural gas	Ruptured
10	Wolverine	16.0	NA	Not exposed, safe
	Toledo-Sarnia	8.0	Propane	Ruptured
	Toledo-Inkster	8.0	NA	Not exposed, safe
16	Line 15	30.0	Natural gas	Not exposed, safe
	Line 10	30.0	Natural gas	Ruptured
	Line 25	36.0	Natural gas	Not exposed, safe
20	Line 15	30.0	Natural gas	Ruptured
	Line 10	30.0	Natural gas	Exposed, safe
	Line 25	36.0	Natural gas	Not exposed, safe
28	Buckeye F-2	NA	Refined products	Not exposed, safe
	Buckeye F-1	NA	Refined products	Not exposed, safe
	Line 20	36.0	Natural gas	Ruptured
30	Line 100-1	34.0	Natural gas	Not exposed, safe
	Line 100-2	34.0	Natural gas	Not exposed, safe
	Line 100-3	36.0	Natural gas	Ruptured

Table 5: Accidents involving underground parallel pipelines(continued).

	Line 100-4	42.0	Natural gas	Ruptured
	Line 100-5	48.0	Natural gas	Exposed, but remained safe
	Line 100-6	48.0	Natural gas	Not exposed, safe
31	Line 100-1	34.0	Natural gas	Not exposed, safe
	Line 100-2	34.0	Natural gas	Ruptured
	Line 100-3	36.0	Natural gas	Exposed, but remained safe
	Line 100-4	42.0	Natural gas	Not exposed, safe
	Line 100-5	48.0	Natural gas	Not exposed, safe
	Line 100-6	48.0	Natural gas	Not exposed, safe
32	Line 1100	26.0	Natural gas	Not exposed, safe
	Line 1103	30.0	Natural gas	Ruptured
	Line 1110	30.0	Natural gas	Not exposed, safe
34	Line 5A	22.0	Natural gas	Not exposed, safe
	Line 5B	24.0	Natural gas	Ruptured
35	NA	39.4	Natural gas	Ruptured
	NA	35.0	Natural gas	Exposed, but remained safe
37	NA	12.0	Abandoned	Exposed, safe
	South Main Line	16.0	Natural gas	Ruptured
41	Line 100	18.0	Natural gas	Ruptured
	Line 200	24.0	Natural gas	Not exposed, safe
	Line 300	30.0	Natural gas	Not exposed, safe
42	R line	26.0	Natural gas	Not exposed, safe
	RA loop line	26.0	Natural gas	Ruptured
43	NA	10.0	Sanitary sewer	Exposed, but remained safe
	Line 132	30.0	Natural gas	Ruptured
	Distribution	4.0	Natural gas	Exposed, but remained safe
45	Line 100-1	24.0	Natural gas	Ruptured
	Line 100-2	30.0	Natural gas	Not exposed, safe
	Line 100-3	NA	Natural gas	Not exposed, safe
	Line 100-4	NA	Natural gas	Not exposed, safe
46	Bonna Vista	8.69	Natural gas	Ruptured
	Nig Creek	16.0	Natural gas	Ruptured
47	SM-86	26.0	Natural gas	Not exposed, safe
	SM-86 loop	30.0	Natural gas	Not exposed, safe
	SM-80	20.0	Natural gas	Ruptured

It can be seen in Table 5 that all accidents involving underground parallel pipelines were caused by gas pipeline ruptures. Sixteen cases out of seventeen, the ruptured pipeline transported natural gas and another pipeline transported propane. Due to the fact that accidents involving gas and liquefied products are prone to form a crater in the ground, if there is any adjacent pipeline in the row, this pipeline can be exposed to the consequences of the accident. Thus, there is a major potential of domino effect for pipelines adjacent to gas and liquefied product pipelines. This fact is confirmed by the real accidents presented in Table 5, because in five cases out of seventeen at least one adjacent pipeline was exposed to the fire inside the crater and to the pressure load during the crater formation. In two of these cases, i.e. the accidents in Rapid City [24] and Buick [12], there was the occurrence of domino effect.

The examination of accidents that occurred in Rapid City and Buick (accidents 30 and 46, respectively) indicated that the domino effects were caused by the thermal load originated from the fire generated by the rupture of the first pipeline.

In the case of Rapid City, the domino effect was confirmed by metallurgical examinations of the failed pipeline sections. The examination of Line 100-4, which ruptured first, confirmed that its rupture resulted of stress overload at a pre-existing defect located at the toe of the longitudinal seam weld, and this stress load is an indicative of external corrosion. Line 100-3 was running adjacent to Line 100-4 and ruptured 52 minutes later. The examination of Line 100-3 confirmed that its rupture resulted from the over-stress caused by heat exposure to the fire generated by the first pipeline rupture. The occuring over-stress lowered the mechanical properties of the pipe to a point that its wall yielded to the stresses from the internal operating pressure. There was another pipeline (Line 100-5) running adjacent to Lines 100-3 and 100-4 operating approximately 100 cm directly under Lines 100-3 and 100-4, which was also exposed to the fire, however this exposure resulted in minor coating damage and the domino effect did not occur in this case. Three other parallel pipelines (Line 100-1, Line 100-2 and Line 100-6) were not exposed to the fire and also remained safe after the accident occurred [24].

In the case of Buick, the analysis of the failed section of Nig Creek pipeline included visual examination, magnetic particle inspection, coating testing, chemical analysis, metallography, mechanical testing and hardness testing. The analysis concluded that the rupture of the aforementioned pipeline was the result of a pre-existing hook crack that caused a fracture along the electric resistance welded longitudinal seam of a pipe joint. The Nig Creek pipeline was running adjacent to Bonavista pipeline and ruptured 25 minutes later. The laboratory analysis of the failed Bonavista pipeline segments included visual examination, chemical analysis, metallography and hardness testing. It was concluded that its failure was the result of over-heating due to fire impingement, which lowered its yield strength, reducing its ability to withstand the internal pressure [12].

The anaysis of real accidents presented in Table 5 also reveals that once the parallel pipeline was not exposed to the crater, which also means that the pipeline was outside of the formed crater, it remained safe after the accident since it was protected by the surrounding soil. Furthermore, other six pipelines were reported in the literature which remained safe after being exposed to the consequences of the accident (see Table 5). These accidents confirm the theoretical point-of-view that the definition of minimum separation distances relying on the crater width is a simple and efficient way of assuring the safety of underground parallel pipelines.

Even though accidents involving other than petroleum product pipelines are outside of the scope of this work, it is important to mention three cases of domino effect caused by water pipelines. The first case is related to an 8 *inch* natural gas pipeline failure occurred in Malaysia in 2009 [25], the second one is related to a 34 *inch* oil pipeline failure occurred in Romeoville, Illinois, USA in 2003 [26], and the third one is also related to an 8 *inch* natural gas pipeline failure occurred in Malaysia in 2012 [27]. Experimental and computational studies have been found in [28, 29, 30, 31] and [32, 33] for the first and third cases, respectively. In these accidents, the domino effect was caused by a high-pressure water jet which in the presence of the surrounding soil produced a highly abrasive slurry. The abrasive jet caused erosion of the coating materials and made the steel pipeline wall thin when impacted on it. The main characteristics of the pipelines involved in these three cases and the description of these accidents were summarized in [7]. One can find guidelines on the safety distance between underground natural gas and water pipelines in [34].

It has been observed in 41 cases out of 48 underground pipeline accidents that the size of the crater width was recorded. It can be seen from these cases that the pipeline diameter and operating pressure are the main pipeline design parameters in the determination of the size of the crater width. In order to have a better understanding on how these parameters have influenced the crater sizes generated in real accidents, Figure 15 shows the crater width generated in actual accidents based on the pipeline diameter and operating pressure, and Figure 16 presents the variation of the crater width with these parameters individually.

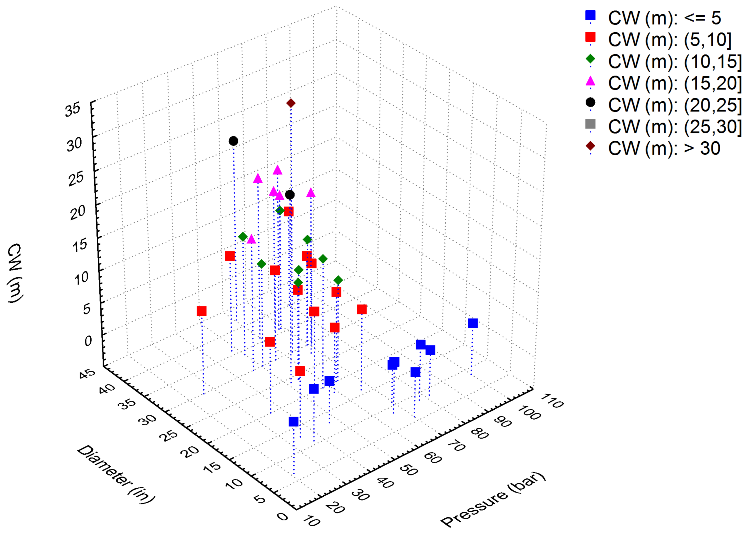
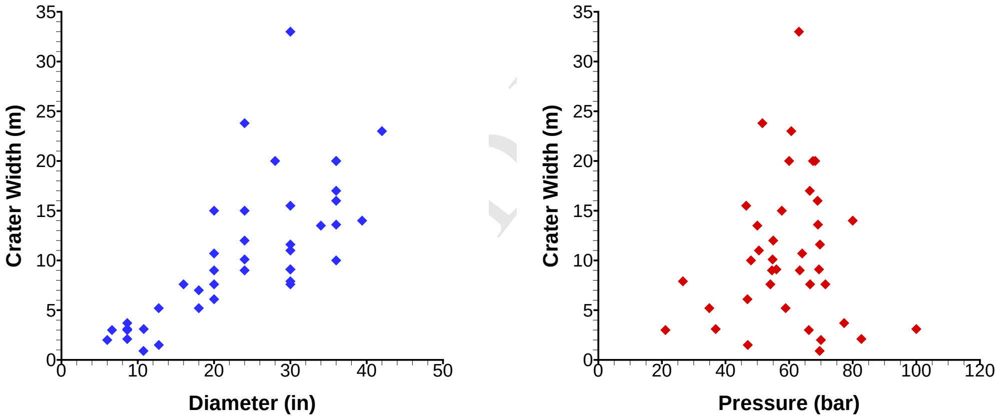


Figure 15: Crater width based on the pipeline pressure and diameter.



(a) Crater width versus pipeline diameter

(b) Crater width versus pipeline operating pressure

Figure 16: Crater width versus pipeline diameter and operating pressure individually.

By analyzing these results, it has been observed that according to actual accidents, the pipeline diameter is the main pipeline parameter influencing the crater width, because the crater width increases significantly with the increment of the pipeline diameter. Considering the variation of the crater width with the operating pressure itself, the increment of the crater width has not been observed in the same way as it can be observed for the pipeline diameter. The impact of the soil type on the size of the crater width is important, therefore no conclusions can be drawn for these pipeline accident results. Furthermore, for smaller pipeline diameters, the pressure has almost no influence in the crater width results. For bigger diameters, the pressure range is not as wide as for smaller ones, thus the operating pressure might have influence on the crater width results. Due to the fact that most of the crater width results are smaller than or equal to 20 meters except for only three cases, which also means 93% of the recorded values, the definition of underground parallel pipeline separations at around 10 meters would be sufficient to ensure a small probability of the domino effect.

4.2. Evaluation of the implemented crater models

In order to evaluate the agreement of the implemented models compared to real accident data, the crater sizes have been calculated. The ratio between the predicted and observed crater width for the seventeen case studies are shown in Figures 17, 18 and 19 for the models from the literature.

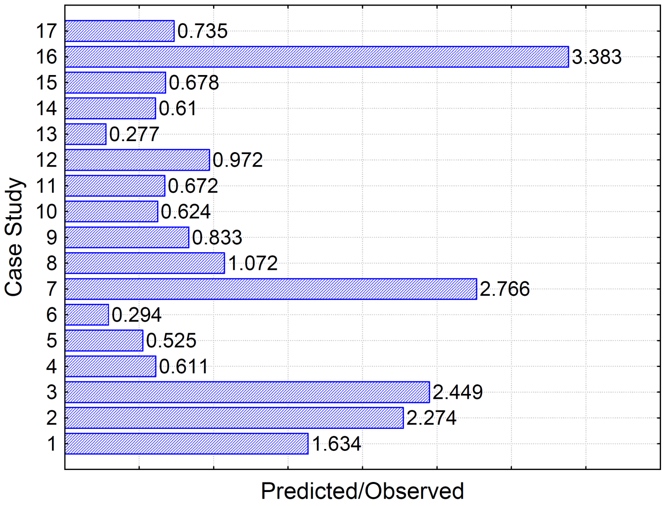


Figure 17: Ratio between predicted and observed crater width for the Gasunie model.

Figure 17 shows that there is not an accurate agreement between the Gasunie model predicted crater width and the observed ones in real accidents. The predicted ones are smaller than the observed values in approximately 65% of the cases (i.e. eleven cases) indicating that the Gasunie model tends to underestimate the size of the crater width. The underestimated ratios between the predicted and observed crater width are in the range from approximately 0.28 to 0.83, and most of the values are in the range of 0.5 to 0.7. The Gasunie model overestimated the crater width in five cases in which most calculated values are more than two times bigger compared to the observed values. In two cases, the predicted values are approximately three times bigger than the observed crater width. One can observe that only two cases exhibit good agreements with real accident data in which the ratio of predicted and observed values is close to unity.

One of the reasons that could explain the inaccurate results predicted by the Gasunie model is that this model was developed relying on experimental data without taking into account the pipeline operating pressure, which is the driving force of the process. Furthermore, this model employs a simple qualitative description of the soil characteristics to determine the soil parameter that is used to represent the moisture and type of the soil. These model features seem to be too simple to represent the interaction between the jet of gas and the soil during the crater formation.

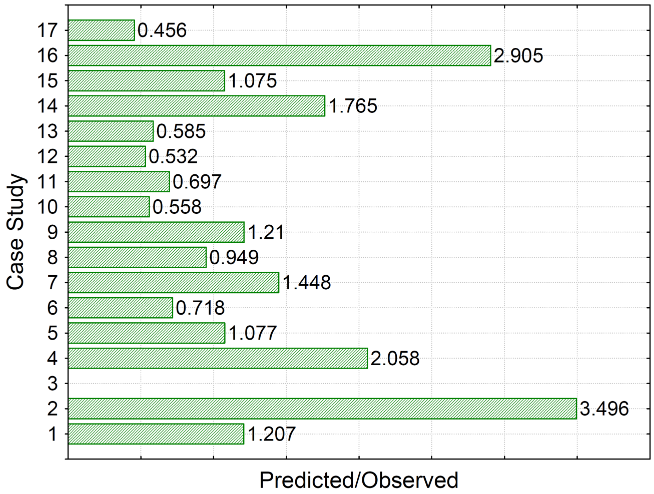


Figure 18: Ratio between predicted and observed crater width for the Advantica model.

It can be seen that the implemented Advantica model shows a slight improvement in the predicted crater width compared to the Gasunie model (see Figure 18). The main reason for this may be the inclusion of the pipeline operating pressure in the model. In the case of this model, there is a balance between the under- and overestimation of the crater width. For those cases where this model underestimates the crater width, ratios between the predicted and observed crater width are in the range from approximately 0.45 to 0.95, and it improves most of the values to the range of 0.6 to 0.7. For those cases where the Advantica model overestimates the crater width, most calculated values are again more than two times bigger compared to the observed values similar to the Gasunie model. In two cases again (see Figure 18), the predicted values are approximately three times bigger than the observed crater width. It can also be observed that only three cases show good agreements with real accident data in which the ratio of predicted and observed values is close to unity, and we can see a slight improvement hereby as well.

In terms of soil characterization, the implemented Advantica model has two shortcomings such as a) considers only qualitative soil characteristics, and b) takes into account only three soil types (sandy, clay and mixed) to represent all different soil environments. These model features can be considered as very restrictive and may have contributed to the inaccurate results predicted by this model. Another disadvantage of the implemented Advantica model for the mixed soil type lies on the fact that the correlation curves are valid for all pressure levels up to a maximum value of 80 bar, which also means that the pipeline diameter is the only variable to influence the crater width prediction in this case. For example, it was not possible to calculate the crater width for case study 3 in which the pipeline operating pressure was equal to 100 bar.

In the case of the Batelle model, there is also not a perfect agreement between the calculated and

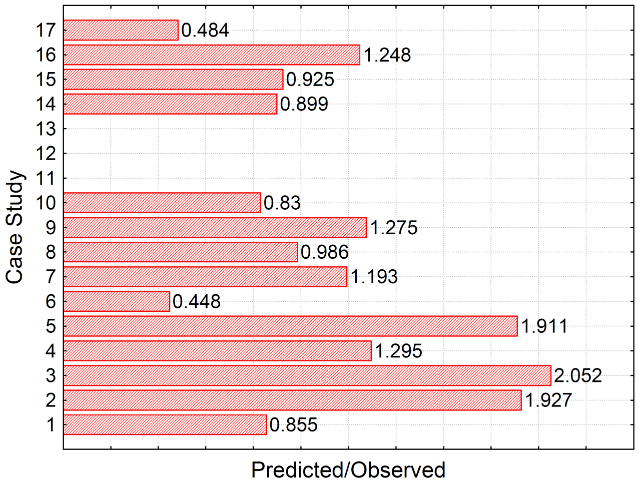


Figure 19: Ratio between predicted and observed crater width for the Batelle model.

the observed crater width, however it is noteworthy that the inclusion of important variables such as the specific heat ratio of the gas, soil density and pipeline operating pressure may have contributed to improve the crater width prediction (see Figure 19). The ratios between the predicted and the observed crater width calculated by using the Batelle model are far closer to unity compared to the ratios predicted by the Gasunie and Advantica models. There is a maximum deviation in the range of -20 to +30% in most cases. The Batelle model also makes an improvement in those cases where there is an overestimation of the crater width, because all predicted ratios are below or close to the values which are two times bigger compared to the observed ones.

As discussed above, we can conclude that the Batelle model can predict more accurately the crater width compared to the other crater models in the literature.

It is important to emphasize the performance evaluation of the Accident-Based model proposed in this paper. The ratios between the predicted and observed crater width obtained by using the proposed model have been shown in Figure 20.

The results show that the proposed Accident-Based model exhibits a better performance compared to other models in this work (see Figure 20). The gained improvements also confirm the hypothesis that the inclusion of all relevant design pipeline parameters as the specific heat ratio of the gas, soil density and pipeline operating pressure in the modelling process contribute to further improve the crater width prediction. The ratios between the predicted and the observed crater width calculated by employing the proposed Accident-Based model are closer to unity compared to the ratios calculated by Gasunie, Advantica and Batelle models.

The Batelle and Accident-Based models can be improved in order to avoid the underestimation of the crater width. In the case of the Batelle model, the parameters that define the crater width have been evaluated and it has been observed that the underestimation of the crater width can almost be overcome by using an average value of 1.8542 for the critical velocity. By applying the

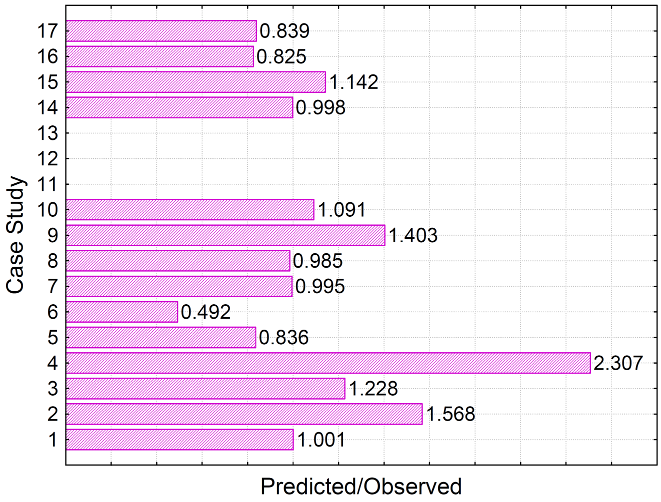
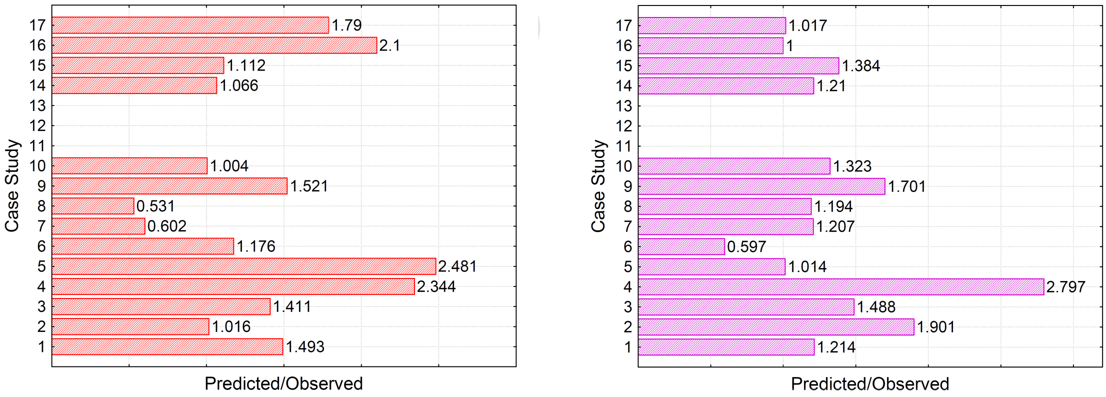


Figure 20: Ratio between predicted and observed crater width for the Accident-Based model.

proposed Accident-Based model, it has been observed that the underestimation of the crater width can also be overcome by using a correction factor of 1.2125. Relying on these assumptions, the 400 Batelle and the proposed Accident-Based models have been modified and most of the obtained ratios between the predicted and observed crater width remained equal or greater than unity as it can be seen in Figure 21.



(a) Batelle model

(b) Accident-Based model

Figure 21: Ratio between predicted and observed crater width for the improved crater models.

The final polynomial formulation for the proposed Accident-Based model can be expressed as

$$CW = 40.795 + 0.382D_p - 0.068P + 4.844D_c - 10.069\gamma - 0.020\rho_{soil}, \tag{15}$$

and overall, it can be concluded that when the design of underground parallel pipelines is concerned, 405 the domino effect can more likely be prevented by the definition of parallel pipelines distances based on the Batelle and Accident-Based models. These models have similar performance, however the

Accident-Based model exhibits sligthly better results compared to the Batelle model.

After considering all advantageous features of the Batelle and Accident-Based models, it is important to mention that their shortcomings are mainly related to the availability of the soil density, which needs to be determined before using these models. This fact can also explain the absence of results for case studies from 11 to 13 in which accidents the soil densities were not available in the literature.

5. Conclusions

The accidents that occurred in the past with crater formation indicate a major potential of domino effect for underground pipelines adjacent to gas and liquefied product pipelines. As it was discussed, two of these accidents occurred with the domino effect suggesting that the risk evaluation of underground parallel pipelines has to consider this possibility.

The anaysis of real accidents that occurred involving underground parallel pipelines revealed that once the parallel pipeline was located outside of the crater formed, it remained safe after the accident because it was protected by the surrounding soil. These investigated accidents confirmed the validation of the theoretical approach that the definition of minimum separation distances based on the crater width is a simple and efficient way of assuring the safety of underground parallel pipelines.

Relying on 41 cases out of 48 accidents investigated in this paper, the crater width was smaller than or equal to 20 meters in 93% of these cases indicating that if the domino effect is not evaluated, the definition of underground parallel pipeline separations at around 10 meters would be sufficient to ensure a small probability of the domino effect.

The crater models from literature predicted different values for the crater width formed by the rupture of a gas pipeline. After comparing the performance of these models, the implemented Advantica model showed a slight improvement compared to the Gasunie model, however the best performance was obtained by using the Batelle model. This is due to the fact that the Batelle model takes into account all important variables as the specific heat ratio of the gas, soil density and pipeline operating pressure in the modeling process.

We present a novel crater model development based on data from real accidents in this paper. A mathematical approach has been developed which allows the prediction of the crater width as a function of the relevant design pipeline parameters such as diameter, depth of cover, operating pressure and the specific heat ratio of the gas transported as well as the soil density.

Modifications have been proposed and implemented to the Batelle and Accident-Based models presented in this paper in order to overcome the underestimation of the crater width.

Relying on real accident data, the performance evaluation of the Accident-Based model proposed in this paper showed that this model has a slightly better performance compared to the Batelle model.

Overall, considering the analysis of different crater models presented in this paper, we can conclude that when the design of underground parallel pipelines is concerned, the domino effect can more likely be prevented by the definition of underground parallel pipelines distances based on the Batelle and Accident-Based models.

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Appendix

Table A1: List of pipeline accidents with crater formation.

ID	Local	year	Product	Pipeline characteristics			Crater dimensions			References
				Diameter (in)	Pressure (bar)	Depth of cover(m)	Length (m)	Width (m)	Depth (m)	
1	Natchitoches, Louisiana, USA	1965	Natural gas	24.0	54.6	1.0	23.0	9.0	4.5	[4, 16, 17, 35]
2	Port Hudson, USA	1970	Propane	8.625	66.2	1.5	3.0	3.0	1.2	[16, 17]
3	Conway, Kansas, USA	1973	Ammonia	8.625	82.73	1.0	2.1	2.1	1.8	[16, 17]
4	Austin, Texas, USA	1973	LNG	10.783	36.9	1.0	3.1	3.1	NA	[16, 17]
5	**Bealeton, Virginia, USA**[1]	**1974**	**Natural gas**	**30.0**	**50.5**	**1.0**	**36.0**	**11.0**	**2.1**	**[4, 16, 17]**
6	Farmington, New Mexico, USA	1974	Natural gas	12.75	34.9	0.76	13.0	5.2	3.0	[16, 17]
7	Monroe, Louisiana, USA	1974	Natural gas	30.0	56.0	1.95	30.0	9.1	7.6	[16, 17]
8	Meridian, Mississipi, USA	1974	NG + Liq+CO_2	6.625	21.1	0.9	3.0	3.0	1.8	[16, 17]
9	Devers, Texas, USA	1975	LPG	8.625	100.0	0.9	3.1	3.1	1.5	[16, 17]
10	**Romulus, Michigan, USA**	**1975**	**Propane**	**8.625**	**77.3**	**NA**	**3.7**	**3.7**	**2.1**	**[16, 17]**
11	Cartwright, Louisiana, USA	1976	Natural gas	20.0	54.1	NA	13.7	7.6	3.1	[4, 16, 17]
12	Long Beach, California, USA	1980	Naphtha	10.75	69.6	0.91	1.2	0.9	0.9	[16, 17]
13	Hudson, Iowa, USA	1982	Natural gas	20.0	57.7	0.91	19.5	15.0	2.8	[16, 17]
14	Jackson, Louisiana, USA	1984	Natural gas	30.0	71.4	0.9	27.5	7.6	3.0	[16, 17, 36]

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[1] Accidents which involved underground parallel pipelines are highlighted in bold.

15	Erlangen, Germany	1984	Natural gas	28.0	67.5	1.0	15.0-20.0	15.0-20.0	3.0-4.0	[4, 17]
16	**Beaumont, Kentucky, USA**	**1985**	**Natural gas**	**30.0**	**69.7**	**1.8**	**27.5**	**11.6**	**3.7**	**[4, 16, 17, 37]**
17	Ignace, Ontario, Canada	1985	Natural gas	36.0	66.5	NA	17.0	17.0	3.0	[16, 17]
18	Lowther, Ontario, Canada	1985	Natural gas	36.0	67.89	NA	28.0	NA	4.9	[16, 17]
19	Callander, Ontario, Canada	1986	Natural gas	36.0	62.61	NA	31.0	NA	4.0	[16, 17]
20	**Lancaster, Kentucky, USA**	**1986**	**Natural gas**	**30.0**	**69.4**	**1.8**	**152 .0**	**9.1**	**1.8**	**[4, 16, 17, 37]**
21	Sabine Pass, Texas, USA	1989	Natural gas	16.0	57.6	0.15	3.0	NA	1.5	[16]
22	Marionville, Ontario, Canada	1990	Natural gas	12.76	47.0	1.2	4.6	1.5	1.7	[16, 17]
23	Cardinal, Ontario, Canada	1991	Natural gas	20.0	63.35	NA	17.8	9.0	2.7	[16, 17]
24	Cochrane, Ontario, Canada	1991	Natural gas	30.0	63.10	NA	49.0	33.0	3.0-7.0	[16, 17]
25	Saskatchewan, Canada [2]	1992	Natural gas	36.0	60.0	1.0	27.0	20.0	6.0	[16, 38]
26	Potter, Ontario, Canada	1992	Natural gas	36.0	69.07	0.91	56.1	13.6	4.5	[16, 17]
27	Palaceknowe, Moffat, Scotland	1993	Natural gas	36.0	48.0	3.0	10.0	10.0	4.0	[4, 17]
28	**Edison, New Jersey, USA**	**1994**	**Natural gas**	**36.0**	**68.2**	**3.7**	**43.0**	**20.0**	**4.3**	**[4, 16, 17, 39]**
29	Latchford, Ontario, Canada	1994	Natural gas	36.0	68.95	0.914	36.0	16.0	2.0-4.0	[4, 16, 17, 40]
30	**Rapid City, Manitoba, Canada** [3]	**1995**	**Natural gas**	**42.0**	**60.68**	**4.0**	**51.0**	**23.0**	**5.0**	**[4, 16, 17, 24]**
31	**Saint Nobert, Manitoba, Canada**	**1996**	**Natural gas**	**34.0**	**50.0**	**1.3**	**17.0**	**13.5**	**5.0**	**[4, 16, 17, 41]**
32	**Carlsbad, New Mexico, USA**	**2000**	**Natural gas**	**30.0**	**46.5**	**NA**	**34.4**	**15.5**	**NA**	**[42]**
33	Viola and New Windsor, Illinois, USA	2003	Natural gas	24.0	55.0	NA	NA	12.0	7.6	[17]

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[2] Experimental test.

[3] The incident Report describes the rupture of a 42 *inch* pipeline followed by a rupture of a 35 *inch* pipeline, indicating a case of domino effect.

34	**Eaton, Colorado, USA**	**2003**	**Natural gas**	**24.0**	**NA**	**NA**	**305.0**	**15.0**	**6.0**	**[17]**
35	**Ghislenghien, Belgium**	**2004**	**Natural gas**	**39.4**	**80.0**	**1.10**	**14.0**	**14.0**	**4.0**	**[11]**
36	Lawrence, Douglas County, Kansas , USA	2005	Natural gas	20.0	46.9	0.6	6.1	6.1	NA	[43]
37	**Elmore County, Alabama, USA**	**2007**	**Natural gas**	**16.0**	**77.8**	**NA**	**NA**	**NA**	**NA**	**[44]**
38	Baden-Wurttemberg, Germany	2007	Natural gas	6.0	70.0	NA	5.0	2.0	2.0	[17]
39	Pilot Grove, Cooper County, Missouri,USA	2008	Natural gas	24.0	54.8	1.8	15.2	10.1	2.1	[45]
40	Bushland, Potter County, TX, USA	2009	Natural gas	24.0	52.5	1.5	17.4	NA	4.3	[46]
41	**Palm City, Florida, USA**	**2009**	**Natural gas**	**18.0**	**58.9**	**1.1**	**35.6**	**5.2**	**0.9**	**[23]**
42	**Abbyville, Reno, Kansas, USA**	**2010**	**Natural gas**	**26.0**	**57.4**	**1.0**	**NA**	**NA**	**NA**	**[47]**
43	**San Bruno, California, USA**	**2010**	**Natural gas**	**30.0**	**26.6**	**NA**	**21.9**	**7.9**	**NA**	**[48]**
44	Gillette, Campbell,Wyoming, USA	2011	Natural gas	30.0	92.4	NA	NA	NA	NA	[49]
45	**Batesville, Panola, Mississippi, USA**	**2011**	**Natural gas**	**24.0**	**51.6**	**3.7**	**23.8**	**23.8**	**4.6**	**[50]**
46	**Buick, British Columbia, Canada**[4]	**2012**	**Natural gas**	**16.0**	**66.6**	**NA**	**17.0**	**7.6**	**1.1**	**[12]**
47	**Sissonville, West Virginia, USA**	**2012**	**Natural gas**	**20.0**	**64.1**	**NA**	**22.9**	**10.7**	**4.3**	**[51, 52]**
48	East Godavari, Andhra Pradesh, India	2014	Natural gas	18.0	NA	5.0	7.0	7.0	7.0	[53, 54]

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[4] The incident Report describes the rupture of a 16 *inch* pipeline followed by a rupture of a 6.625 *inch* pipeline, indicating a case of domino effect.

Highlights

- Pipeline crater models from literature have been evaluated relying on real accidents.
- A historical analysis of accidents involving underground pipelines has been performed.
- A FORTRAN code to assess the performance of the crater models has been designed.
- A specific novel pipeline crater model has been developed by using data from real accidents
- The potential of domino effect is proven by two real cases.
- Parallel pipeline distance values are suggested to prevent the domino effect.