|  |  |
| --- | --- |
| cetlogo ***CHEMICAL ENGINEERING TRANSACTIONS***  ***VOL. xxx, 2025*** | A publication of  aidiclogo_grande |
| The Italian Association  of Chemical Engineering  Online at www.cetjournal.it |
| Guest Editors: Bruno Fabiano, Valerio Cozzani  Copyright © 2025, AIDIC Servizi S.r.l. **ISBN** 979-12-81206-xx-y; **ISSN** 2283-9216 | |

Modelling Crater Formation and Gas Dispersion Following Buried Pipeline Ruptures

Paul Brasser, Rik van Haaften, Andreas Mack

Gexcon Netherlands BV

Corresponding author: paul.brasser@gexcon.com

As environmental concerns continue to grow, storage of CO₂, in depleted gas fields is an option. This requires transporting the CO2, which is commonly done through pipelines where it is liquefied under high pressure. In scenarios where a buried pipeline ruptures, pressurized gases are rapidly released, forming a crater and creating a significant dispersion risk. This paper introduces a crater formation model implemented in EFFECTS, a consequence modeling tool developed by Gexcon, that predicts both crater dimensions and the behavior of the exit jet for use in dispersion modeling. The Webber model is used for describing the release from the rupture of a long pipeline and integrating Cleaver and Defined Area models for the crater estimation. This study validates the model against both experimental data and real accident cases. Results show a good agreement between modeled and observed data. Sensitivity analysis is used to find the variables that influence outcomes the most.

* 1. Introduction

Buried pipelines transporting substances like liquefied CO₂ can experience full bore ruptures, leading to the formation of a crater when the pressurized content is released. To address this, EFFECTS includes Webber’s model for simulating outflow dynamics from long pipelines area (Van Haaften et al. 2024). Furthermore, EFFECTS integrates the Cleaver and Defined Area models for crater formation and exit jet prediction from Crater (Brasser 2024). This approach provides the necessary source terms for EFFECTS' dispersion model, while taking into account the buoyant properties of CO2, thereby improving predictions for safety and environmental impact analysis.

* 1. Theoretical Background

2.1 Pipeline Rupture Modeling

EFFECTS uses Webber’s long pipeline model to simulate the two-phase flow that occurs during a pipeline rupture. This model starts with an isothermal pressure drop to vapor pressure, followed by choked flow behavior within a two-phase regime that progresses along the pipeline. This model predicts temperature and pressure variations and the resulting prediction of flow rate, vapor fraction, and thermodynamic state throughout the rupture event (Van Haaften et al. 2024).

2.2 Crater Formation Model

After pipeline rupture, crater formation is dependent on characteristics such as the leak type, soil properties, and pipeline depth. The Crater Model predicts parameters such as crater width, depth, and surface area using approaches from Cleaver and the Defined Area model. These models were chosen based on their ability to simulate both punctures and full-bore ruptures, and their capability to predict the agent mass fraction of the exit jet (Brasser 2024). Apart from the depth of the pipe in the ground, the depth of the release is dependent on the type of leakage, (Cleaver et al. 2015) The various variable names are described in the nomenclature.

|  |  |
| --- | --- |
|  | (1) |

The crater width is dependent on soil type. The following empirical equation is assumed:

|  |  |
| --- | --- |
|  | (2) |

The fit constants (a, b, c, d) for this equation are given in (Cleaver et al. 2015) for various soil types. The length of the crater can be larger than the width when a pipeline fracture occurs (in contrast to a puncture):

|  |  |
| --- | --- |
|  | (3) |

The depth of the crater depends on the release depth and the type of soil:

|  |  |
| --- | --- |
|  | (4) |

The fit constants K1 and K2 are given in (Cleaver et al. 2015) for various soil and leak types.

The total area of the crater is determined by:

|  |  |
| --- | --- |
|  | (5) |

The effective outflow area of the outflow jet (assumed to be circular shaped) can be much smaller than the crater area and is and dependent on the width of the crater and the diameter of the expanding jet:

|  |  |
| --- | --- |
|  | (6) |

Which leads to an effective area of:

|  |  |
| --- | --- |
|  | (7) |

The crater volume will be calculated by EFFECTS and can be interesting in case of liquid leakage, filling the crater. This liquid can form a liquid pool, which can potentially evaporate. To calculate the volume of the crater, the surface area of the crater is integrated over the depth. To make the surface area calculation dependent on the depth of the crater, the area is defined in a slightly different way, namely as stadium shape:

|  |  |
| --- | --- |
|  | (8) |

Where the depth dependent radius, r is determined by:

|  |  |
| --- | --- |
|  | (9) |

and the depth dependent length of the square, L0, is determined by:

|  |  |
| --- | --- |
|  | (10) |

Here, the index z indicates the value of the length and width at the depth z of the crater. The depth of the crater is assumed to have a parabolic form:

|  |  |
| --- | --- |
|  | (11) |

Or:

|  |  |
| --- | --- |
|  | (12) |

The volume follows from integrating the area over the depth:

|  |  |
| --- | --- |
|  | (13) |

By substituting Anew and r and integrating over the depth, it can be found that:

|  |  |
| --- | --- |
|  | (14) |

Since the area was calculated slightly different, this volume is corrected toward the other area size definition by:

|  |  |
| --- | --- |
|  | (15) |

* + 1. Crater outflow

Two possible approaches can be used to calculate the outflow of agent from the crater:

* Cleaver (Cleaver et al. 2015)
* Defined Area model (Mike Harper, Witlox, and Fernandez 2023).
* The main difference is the way the agent fraction in the outflow is estimated. The Cleaver model will be used here for puncture leakages, while the Defined Area model will be used for full-bore ruptures.

Cleaver model

The mass fraction of agent in the jet is defined as:

|  |  |
| --- | --- |
|  | (16) |

The Cleaver solution uses an empirical relation to estimate the mass fraction at the exit of the crater. This relation is dependent on the dimensionless path length of the agent from the pipe to the exit of the crater:

|  |  |
| --- | --- |
|  | (17) |

The empirical relation for is:

|  |  |
| --- | --- |
|  | (18) |

Defined area model

The Defined area model uses a different empirical model for the mass fraction (named f, instead of ηpol0 to show the difference) of pollutant, dependent on the fracture length. In case of a puncture, as mentioned before, the relation of Cleaver will be used. The defined area to calculate the agent mass fraction is:

|  |  |
| --- | --- |
|  | (19) |

The mass flow rate out of the crater follows from the sum of the outflows from the two pipes (Mike Harper et al. 2023)

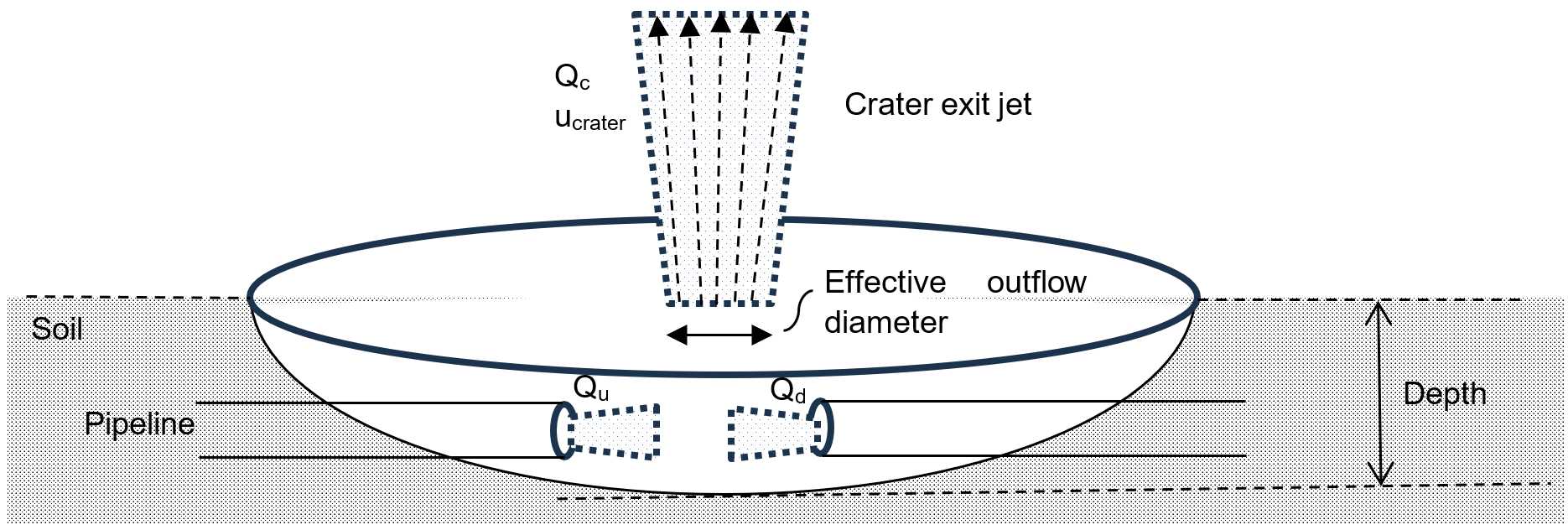


Figure 1 Side view of a crater, depicting the pipeline outflows and the effective outflow jet, out of the crater.

The air entrainment to the jet is calculated by using the above defined mass fraction:

|  |  |
| --- | --- |
|  | (20) |

The mass flow rate of entrained air follows from:

|  |  |
| --- | --- |
|  | (21) |

3. Model Validation

3.1 Crater size validation

Validation was conducted using data from the COSHER project, which involved large-scale CO₂ pipeline rupture experiments (Ahmad et al. 2015), (Pham and Rusli 2016). These tests provided measurements of crater dimensions and CFD based crater exit flow conditions. The proposed Crater Model was validated by calculating the crater dimensions and jet release, based on the pipeline release, as measured in the COSHER project. Since the type of soil was not given in the experimental description, the calculations were performed for all three types of soil, existing in the crater model.

By plotting the crater, as is calculated by the model on top of the experimental measurements, a good insight can be given into the predictive performance of the model in terms of crater dimensions. Both these experimental and calculated dimensions of the formed crater are represented in a top and sideview as shown in Figure 2.

A graph showing different sizes of objects

Description automatically generated with medium confidence A graph of different sizes and colors

Description automatically generated

Figure 2 Top view of measured and calculated width and length of the crater (left) and measured and calculated depth and width of the crater (right). Measurements from (Ahmad et al. 2015).

As can be seen from Figure 2, the model predicts crater sizes in the same order of magnitude as the measurements, though the sandy soil calculations predict a too large crater. The mixed soil calculations show a very good agreement for the width calculations (at both sides of the width of the crater), while the length of the crater is best predicted by the clay soil type calculations. As the type of soil in the experiments was not specified in the article, these calculated results were considered to be in very good agreement with the measurements. A similar result for the depth calculations was found. The shape of the crater was best described by the mixed soil type, while the absolute value of the depth in the centre of the crater was best described by the clay soil type. Again, these results were interpreted to be in very good agreement with the experimental results.

In addition to experimental data, the Crater Model was validated using historical accident data involving releases of CO₂ and other liquefied gases. Model predictions for crater depth only differed 2 % to 11% in size compared to the available data, thus EFFECTS’ predictions show good agreement with observed data.

Table 1 Crater dimensions of craters, formed by accidents with Liquefied gas (Silva et al. 2016),(Hse 2002), (Konersmann, Kühl, and Ludwig 2009) (L = Length, W = Width, D = Depth).

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Accident |  |  | Measured |  |  | Calculated |  |  |
| Location | year | Product | L (m) | W (m) | D (m) | L (m) | W (m) | D (m) |
| Conway, Kansas, USA | 1973 | Ammonia | 2.1 | 2.1 | 1.8 | 1.91 | 1.91 | 1.16 |
| Austin, Texas, USA | 1973 | LNG | 3.1 | 3.1 | NA | 3.03 | 3.03 | 1.51 |
| Devers, Texas, USA | 1975 | LPG | 3.1 | 3.1 | 1.5 | 3.21 | 3.21 | 1.5 |

3.2 Crater exit validation

To validate the flow exiting the crater for both ruptures and punctures, model calculations were compared with results from CFD calculations (Wareing et al. 2014), (Mike Harper et al. 2023). For rupture leakages, the mass fraction as a function of the non-dimensional path length were given in (Cleaver et al. 2015). In Figure 3 these results are plotted in combination with model calculations.

A graph with a line and a line

Description automatically generated A graph with a line and a line

Description automatically generated

Figure 3 Results from experiments and from CFD calculations (Wareing et al. 2014) compared to the model calculations of the agent mass fraction at the exit of the crater for ruptures (left) and punctures (right).

As can be seen from Figure 3, good agreement was found between model calculations and CFD results of agent fractions for ruptures and a reasonable agreement was found for punctures.

4. Sensitivity Analysis

Sensitivity analysis was conducted to assess the impact of various parameters on crater formation and exit jet behavior. The results indicate a strong correlation between rupture length and both crater depth and outflow rate. For rupture lengths exceeding 2 meters, crater depth and width increased linearly.

A graph of a graph with different colored lines

Description automatically generated with medium confidenceA graph of different colored lines

Description automatically generated with medium confidence

Figure 4 The crater width, length and depth as a function of the rupture length (left) and the total outflow rate of the crater jet and the air entrained rate as a function of the rupture length of the pipeline (right).

Soil composition was shown to have a significant effect on crater dimensions, with sandy soils yielding the largest craters, followed by mixed and clay soils.

A graph showing the size of soil

Description automatically generated A graph of different sizes and colors

Description automatically generated

Figure 5 Crater sizes as function of the soil type (left) and as function of the pipeline depth (right).

Crater size was also found to increase with pipeline depth. Additionally, pipeline depth influenced the jet’s exit velocity, with greater depths leading to higher exit speeds.

5. Conclusion

This paper presents a model for predicting the formation of craters following from buried pipeline ruptures. The EFFECTS Crater Model was validated using both experimental data and historical accident data. The model showed good agreement between experimental data and calculated data of crater dimensions, The model predictions also agree well with the crater exit properties with CFD calculations. Sensitivity analysis showed the effect of pipeline rupture length, pipeline depth and soil type onto the crater dimensions and onto the crater exit jet.

Nomenclature

a,b,c,b - Fit constants for type of soil -

Wcrater - Crater width, m

Hrelease - Release depth, m

Lfracture - Length of the fracture, m

DfT - Diameter of expanded jet, m

Lcrater - Length of the crater, m

Acrater - Area of the crater, m2

Aflow - Effective outflow area from the crater, m2

Dflow - Effective diameter of flow from crater, m

S - Shape factor of the crater, -

Hpipe - Depth of the pipe, m

Dpipe - Diameter of the pipe, m

K1 - Fit constant for type of soil and leakage type, -

K2 - Fit constant for type of soil and leakage type, -

αcrater - Fraction of crater used by outflow, -

MfT - Momentum of expanded jet, kg.m

mpol - Mass release rate, kg/s

ufT - Velocity of expanded jet, kg

mair - Mass flow rate of entrained air, kg/s

- Richardson number, -

uflow - Velocity of jet at the exit of the crater, m/s

uND - Non - dimensional wind speed, -

uND,crit - Critical non - dimensional wind speed, -

u10 - Wind speed at 10 m height, m/s

ηpol0 - Pollutant mass fraction at the crater exit, -

f - Pollutant mass fraction at the crater exit, -

Qc - Mass flow rate of the jet at the exit of the crater, kg/s

Qu - Mass flow rate at exit of pipe, kg/s

Qd - Mass flow rate at exit of pipe, kg/s

Qwa - Mass flow rate of entrained air, kg/s

ρcrater - Density of the jet at exit of crater, kg/m3

g - Gravity constant (9.81), m/s2

- Reduced gravity of the crater outflow, m/s2

References

Ahmad, Mohammad, Barbara Lowesmith, Gelein De Koeijer, Sandra Nilsen, Henri Tonda, Carlo Spinelli, Russell Cooper, Sigmund Clausen, Renato Mendes, and Onno Florisson. 2015. “COSHER Joint Industry Project: Large Scale Pipeline Rupture Tests to Study CO2 Release and Dispersion.” *International Journal of Greenhouse Gas Control* 37:340–53. doi: 10.1016/j.ijggc.2015.04.001.

Brasser, Paul. 2024. *Crater Formation Due to Buried Pipeline Rupture Model, Theoretical Background And Validation Report*. Utrecht, The Netherlands.

Cleaver, Phil, Ann Halford, Tim Coates, Harry Hopkins, and Julian Barnett. 2015. “Modelling Releases of Carbon Dioxide from Buried Pipelines.” in *SYMPOSIUM SERIES NO 160, Proceedings of HAZARD 25*.

Van Haaften, Rik, Sonia Ruiz Pérez, Andreas Mack, and Sonia Ruiz Perez. 2024. *Title Liquefied Gas from Long Pipeline Model, Theoretical Background & Validation Report*. Utrecht, The Netherlands.

Hse. 2002. *HSE Health & Safety Executive Report on a Second Study of Pipeline Accidents Using the Health and Safety Executive’s Risk Assessment Programs MISHAP and PIPERS*.

Konersmann, Rainer, Christiane Kühl, and Jörg Ludwig. 2009. “On the Risks of Transporting Liquid and Gaseous Fuels in Pipelines.”

Mike Harper, M. Witlox, and M. Fernandez. 2023. *The Model CRATER Models the Formation of a Crater from a Buried Long Pipeline.*

Pham, Loi Hoang Huy Phuoc, and Risza Rusli. 2016. “A Review of Experimental and Modelling Methods for Accidental Release Behaviour of High-Pressurised CO2 Pipelines at Atmospheric Environment.” *Process Safety and Environmental Protection* 104:48–84.

Silva, Edmilson P., Marcio Nele, Paulo F. Frutuoso e Melo, and László Könözsy. 2016. “Underground Parallel Pipelines Domino Effect: An Analysis Based on Pipeline Crater Models and Historical Accidents.” *Journal of Loss Prevention in the Process Industries* 43:315–31. doi: 10.1016/j.jlp.2016.05.031.

Wareing, Christopher J., Michael Fairweather, Samuel A. E. G. Falle, and Robert M. Woolley. 2014. “Modelling Punctures of Buried High-Pressure Dense Phase CO2 Pipelines in CCS Applications.” *International Journal of Greenhouse Gas Control* 29:231–47. doi: 10.1016/j.ijggc.2014.08.012.