# Appendix A

Table A1. Summary of the computational models collected in this review. The leaking gas is natural gas represented by methane, unless otherwise specified. Dashes (-) are placed to indicate missing information (possibly not modeled).

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Authors** | **Model** | **Software** | **EOS** | **Soil modelling** | **Soil nature** | **Hole diameter** | **Pressure[[1]](#footnote-1)/ flow** | **Turbulence** | **Validation/**  **Verification** | **Evaluated leak rate** | **Parameters varied/**  **evaluated** |
| [Catlin et al. (1998)](#_ENREF_18) | 3D, ss | ANSYS CFX | CP | None | None | Rupture  Puncture 100 mm | 2.5 - 12.5 bar | - | - | Input to the model | Failure mode, crater configuration, spreading rate in ground, mixing type, release pressure |
| [Cui et al. (2014)](#_ENREF_23) | 2D, tr | ANSYS Fluent | - | Isotropic dry porous media | One kind with given properties | 50 mm and 100 mm | 9 bar | Standard k-ε | - | N | Hole diameter |
| [Foissac et al. (2014)](#_ENREF_35) | 3D, tr + ss | TAGS | - | Isotropic dry porous media | One kind with given properties (sand) | 1 mm, 5 mm | 0.04 - 15 bar | - | [Foissac et al. (2014)](#_ENREF_35) | N | Pressure, hole diameter, testbed and soil textural configurations |
| [Deepagoda et al. (2016)](#_ENREF_25)[[2]](#footnote-2) | 2D, ss | TOUGH2/ EOS7CA | PR | Isotropic partially saturated porous medium with variable saturation | Silica sand (homogeneous), silica sand + coarse-textured sand (layered) | Point source of gas | ~0.038 kg/h | - | [Deepagoda et al. (2016)](#_ENREF_25) | N | Soil textural configuration, water saturation, atmospheric temperature |
| [Ebrahimi-Moghadam et al. (2016)](#_ENREF_29) | 2D, ss | ANSYS Fluent | Ideal | Isotropic dry porous medium | One kind with given properties | 5 - 80 mm | 2 - 4 bar | Standard k-ε | [Montiel et al. (1998)](#_ENREF_64) | Y | Pressure, pipe diameter, hole diameter |
| [Silva et al. (2017b)](#_ENREF_82) | 2D + 3D, tr | ANSYS Fluent | InCP | None | None | Rupture | 66.6×103 kg/h, 110.88×103 kg/h, 195.12×103 kg/h | Standard k-ε | [Lowesmith and Hankinson (2013)](#_ENREF_59) | Input to the model | Fire radiation and flame characteristics |
| [Silva et al. (2017a)](#_ENREF_81) | 2D + 3D, tr | ANSYS Fluent | InCP | None | None | Rupture | Up to 500 m/s | Standard k-ε | [[3]](#footnote-3) | N | Gas velocity, wall thickness  Evaluate pipe cooling effect, radiation and stress |
| [Ebrahimi-Moghadam et al. (2018)](#_ENREF_28) | 3D, ss | ANSYS Fluent | Ideal | Isotropic dry porous medium | One kind with given properties | 5 - 80 mm | 2 - 4 bar | Standard k-ε | [Montiel et al. (1998)](#_ENREF_64) | Y | Pressure, pipe diameter, hole diameter |
| [Deng et al. (2018)](#_ENREF_27) | 2D + 3D, ss + tr | ANSYS Fluent | InCP | Isotropic dry porous medium for low pressure, No soil for high pressure | One kind with given properties | 20 - 100 mm | 10, 50, 100 bar | Realizable k-ε | [Davies and Singh (1985)](#_ENREF_24) | N | Pressure, soil porosity, hole diameter, wind speed  Evaluate consequence distance[[4]](#footnote-4) |
| [Guo et al. (2018)](#_ENREF_37) | 3D, tr | ANSYS Autodyn and MATLAB | Ideal | Isotropic solid with deformation characteristics | Mixed soil: mixture of sand and clay in different proportions | ~27.64 mm | 59 bar | - | Empirical formula for the shock wave peak, eq. (14) | Input to the model | Spacing between parallel pipes, pipe thickness  Evaluate displacement, deformation, overpressure |
| [Bezaatpour et al. (2020)](#_ENREF_12)[[5]](#footnote-5) | 3D, tr | COMSOL | SRK | Anisotropic heterogeneous partially saturated multilayer porous medium | 4 layers of soil: combination of different loam and clay loam textures | 10 - 50 mm | 2 - 4 bar | Reynolds stress model | [Ebrahimi-Moghadam et al. (2018)](#_ENREF_28) | Y | Pressure, pipe diameter, hole diameter, soil water saturation, anisotropy, soil layer slope |
| [Cho et al. (2020)](#_ENREF_20) | 3D, ss | TOUGH3/ EOS7CA | PR | Isotropic partially saturated porous medium | Fine sand to loamy fine sand | Point source of gas (6.4 mm) | 0.01 - 0.3 kg/h | - | [Cho et al. (2020)](#_ENREF_20) | Y | Testbed configuration, flow rate (input and later deduced by the model) |
| [Ndalila et al. (2020)](#_ENREF_67)[[6]](#footnote-6) | 3D, tr | ANSYS Fluent | Ideal | Isotropic dry porous medium | Clay | 10 mm | 4.6 m/s | Standard k-ε | - | N | Velocity |
| [Zhuohua et al. (2020)](#_ENREF_122) | 3D, tr | ANSYS/ LSDYNA | Ideal | Isotropic solid with deformation characteristics | One kind with given properties | 40 mm | 3 bar | - | [Zhong et al. (2018)](#_ENREF_113) | Input to the model | Explosive equivalent, burial depth  Evaluate deformation, stress, energy, overpressure |
| [Wang et al. (2020)](#_ENREF_95) | 3D, tr | COMSOL | Ideal | Isotropic partially saturated porous medium | Uniform sandy and multi-layered soils | 5 mm | 0.9727 – 1.7500 bar | Not modelled | [Yan et al. (2015)](#_ENREF_103) | Input to the model | Pressure, leak direction, soil textural configuration and porosity structure, convective mass transfer coefficient (wind effect) |
| [Zhang et al. (2021b)](#_ENREF_107) | 3D, tr | GB50494- 2009 | Ideal | Isotropic homogeneous dry porous medium | 3 kinds: sand, loam, clay | 10 mm | 1 - 3 bar | DES with Spalart-Allmaras model | [Yan et al. (2015)](#_ENREF_103) | N | Pressure, soil type  Evaluate risk area[[7]](#footnote-7) |
| [Hu et al. (2021)](#_ENREF_44) | 3D, tr | - | - | Isotropic dry porous medium | One kind with given density and different porosities | 3 - 20 mm | 29 - 119 bar | - | Theoretical formula of gas flow from a hole , eq. (1) | Y | Pressure, hole diameter, soil porosity  Evaluate safety distance[[8]](#footnote-8) |
| [Liu et al. (2021)](#_ENREF_57) | 3D, ss + tr | ANSYS Fluent | - | Isotropic dry porous medium | Brown loam (with different soil particle diameters and porosities) | 1 - 4 mm | 0 - 5 bar | Standard k-ε | [Liu et al. (2021)](#_ENREF_57) | Y | Pressure, burial depth, hole diameter, soil properties, temperature, hole shape |
| [Wang et al. (2021b)](#_ENREF_97) | 3D, tr | ANSYS Fluent | Ideal | Isotropic homogeneous dry porous medium | 3 kinds: sand, loam, clay | 5 - 15 mm | 2 - 4 bar | DES with Spalart-Allmaras model | [Yan et al. (2015)](#_ENREF_103) | Y | Pressure, hole diameter, leak direction, soil type  Evaluate alarm time[[9]](#footnote-9) |
| [Bu et al. (2021b)](#_ENREF_17) | 3D, tr | ANSYS Fluent | Ideal | Isotropic dry porous medium | 3 kinds: sand, loam, clay | 20 - 60 mm | 2 - 4 bar | Standard k-ε | [Yan et al. (2015)](#_ENREF_103) | N | Pressure, hole diameter, burial depth, pipe diameter, leak direction, soil type  Evaluate FDT[[10]](#footnote-10), FDR[[11]](#footnote-11) and GDR[[12]](#footnote-12) |
| [Bu et al. (2021a)](#_ENREF_16) | 3D, ss + tr | ANSYS Fluent | Ideal | Isotropic dry porous medium | 3 kinds: sand, loam, clay | 5 - 80 mm | 2 - 4 bar | Standard k-ε | [Yan et al. (2015)](#_ENREF_103); [Ebrahimi-Moghadam et al. (2018)](#_ENREF_28) | Input to the model | Pressure, hole diameter, burial depth, soil type, surface ground type  Evaluate MID[[13]](#footnote-13), MILS[[14]](#footnote-14), MILD[[15]](#footnote-15) |
| [Shanujah et al. (2021)](#_ENREF_77) | 2D, ss | TOUGH2/ EOS7CA | PR | Isotropic partially saturated porous medium with variable saturation | Aggregated soils from sandstone and conglomerate | 10 mm \* 10 mm | 6 - 24 L/min | - | [[16]](#footnote-16) | Input to the model | Flow rate, soil water saturation |
| [Gao et al. (2021)](#_ENREF_36)[[17]](#footnote-17) | 2D, tr | TOUGH2/ EOS7CA | PR | Isotropic partially saturated porous medium with variable saturation | Sand for homogeneous, sand + clay for layered | Point source of gas (6.35 mm) | 0.5, 0.85 kg/h | - | [[18]](#footnote-18) | Input to the model | Flow rate, soil textural configuration, soil water saturation  Evaluate advective and diffusive fluxes |
| [Srour et al. (2022)](#_ENREF_85) | 3D, tr | ANSYS Fluent | InCP | Eulerian-Eulerian-KTFG-granular material | One kind with given properties (sand) | 12 mm | 0.35 - 75 bar | Standard k-ω | [Bonnaud et al. (2018)](#_ENREF_13); [Houssin-Agbomson et al. (2018)](#_ENREF_43) | N | Pressure, burial depth, leak direction |
| [Bagheri and Sari (2022)](#_ENREF_11)[[19]](#footnote-19) | 3D, ss | ANSYS Fluent | PR | Isotropic dry  porous media | 3 kinds: silt, sand, gravel | 2 - 40 mm | 1 - 99 bar | Standard k-ε | [Liu et al. (2021)](#_ENREF_57) | Y | Pressure, pipe diameter, hole diameter, soil porosity, particle diameter |
| [Bu et al. (2022)](#_ENREF_15) | 3D, tr | ANSYS Fluent | Ideal | Isotropic dry  porous media | 3 kinds: sand, loam, clay | 0 - 80 mm | 2 - 4 bar | Standard k-ε | [Yan et al. (2015)](#_ENREF_103); [Shen (2019)](#_ENREF_79) | N | Pressure, hole diameter, burial  depth, soil type, wind speed,  building floor and building combination type  Evaluate FDZ[[20]](#footnote-20) and SDZ[[21]](#footnote-21) |
| [Wang et al. (2022)](#_ENREF_98) | 3D, tr + ss | ANSYS Fluent | Ideal | Isotropic dry  porous media | Loam | 20 - 60 mm | 2 - 4 bar | Standard k-ε | [Okamoto and Gomi (2011)](#_ENREF_68) | N | Pressure, hole  diameter, and minimum construction distance between pipeline and confined space  Evaluate underground adjacent confined space hazardous boundary[[22]](#footnote-22) |
| [Ren et al. (2022)](#_ENREF_75) | 3D, tr + ss | COMSOL | Ideal | Isotropic dry  porous media | Sand or clay for homogeneous and multi-layered soils (including cement, concrete, …) | 5 - 15 mm | 0.5 - 2 bar | - | [Ren et al. (2022)](#_ENREF_75) | Y | Pressure, hole diameter, soil porosity, particle diameter, soil textural configuration and temperature  Evaluate dangerous radius[[23]](#footnote-23) |
| [Wang et al. (2023a)](#_ENREF_94) | 3D, tr | FLACS | Ideal | - | - | Rupture | 10 bar | Standard k-ε | - | N | Wind speed, building monitoring location, detonation distance from building  Evaluate thermal radiation, overpressure, flame dimensions |
| [Xia et al. (2023)](#_ENREF_100) | 3D, tr | ANSYS Fluent | SRK | Isotropic dry  porous media | 3 kinds: sand, loam, clay in box culvert[[24]](#footnote-24), and loam in the outer soil bed | 10 - 30 mm | 60 - 100 bar | Standard k-ε | [Ren et al. (2022)](#_ENREF_75) | Y | Pressure, hole diameter, soil type in box culvert  Evaluate FHT[[25]](#footnote-25), FHD[[26]](#footnote-26), LHD[[27]](#footnote-27) |
| [Su et al. (2023)](#_ENREF_86)[[28]](#footnote-28) | 3D, tr | ANSYS Fluent | Ideal | Isotropic dry porous media | 3 kinds: sand, loam, clay | 10 - 40 mm | 1 - 3 bar | Standard k-ε | [Yan et al. (2015)](#_ENREF_103) | N | Hydrogen blending ratio, pressure, soil type, hole diameter and leak direction  Evaluate FDT10, FDR11 and GDR12 |
| [Zhang and Zhao (2023)](#_ENREF_108)[[29]](#footnote-29) | 3D, tr | - | Ideal | Isotropic dry porous media | 2 kinds: sand and clay | 20 - 40 mm | 10 - 40 bar | Standard k-ε | [Zhou (2018)](#_ENREF_117) | N | Pressure, pipe diameter, hole diameter, soil type |
| [Wang et al. (2023b)](#_ENREF_96)[[30]](#footnote-30) | 3D, tr | OLGA (and MATLAB) | Ideal | None | None | 100 mm | 30 - 60 bar | - | [Zhu et al. (2023)](#_ENREF_121) | Y | Pressure, hydrogen blending ratio, heat transfer coefficient  Evaluate critical parameters (time, pressure, flow) |
| [Jiang et al. (2023)](#_ENREF_47) | 3D, tr | ANSYS Fluent | CP | Isotropic dry porous media | One kind with given properties | 1 mm | 40 bar | Standard k-ε | [Jiang et al. (2023)](#_ENREF_47) | N | [[31]](#footnote-31) |
| [Zeng et al. (2023)](#_ENREF_105) | 3D, tr | ANSYS Fluent | InCP | Isotropic dry porous media | One kind with given properties | 2 - 12 mm | 2 - 12 bar | Realizable k-ε | [Zeng et al. (2023)](#_ENREF_105) | N | Pressure, hole diameter, leak direction, parallel pipeline leak pressure, parallel pipeline leak direction  Evaluate explosive range volume[[32]](#footnote-32) |
| [Jayarathne et al. (2023)](#_ENREF_46) | 2D, tr | COMSOL | PR | Isotropic partially saturated porous medium with variable saturation | Mineral soil (rural), sand (homogeneous), sand + clay (layered) | Point source of gas (6.35 mm) | 5 - 21 sL/min | - | [[33]](#footnote-33) | Input to the model | Leak rate, soil type, testbed and soil textural configuration, soil water content, diffusivity |

Table A2. Experimental-based studies on the topic of underground gas releases.

|  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- |
| **Study** | **Scale** | **Gas released** | **Burial depth** | **Pressure/flow range** | **Release type/ dimension** | **Parameters varied/results obtained** | **Fundamental models** |
| [Hoff (1983)](#_ENREF_41) | Full | Natural gas: 90% methane, 4.4% CO2, 4.2% N2, rest HC | 1 m | 60 bar | Rupture | Pressure wave, plume and crater dimensions, and weather conditions | simple monopole  model |
| [Schram (1991)](#_ENREF_76) | Unavailable study reported to perform experimental investigations and suggest correlations by Delft Hydraulics  Laboratory, sponsored by a transmission pipeline company in the Netherlands | | | - | Rupture | Crater width as function of pipe diameter, depth of cover, and qualitative soil description | - |
| [Wakoh and Hirano (1991)](#_ENREF_92) | Full | Liquified petroleum gas | 0.61 m | 6, 12, 18 L/min | 6 mm | Spatial and temporal gas concentration distribution profiles for various volumetric flows and weather conditions | Fickian diffusion |
| [Abu‐El‐Sha'r and Abriola (1997)](#_ENREF_1) | Small | Helium, carbon monoxide and nitrogen | - | Up to ~0.013 m/s[[34]](#footnote-34) | Point source of gas (3.18 mm) | Plots of diffusion related parameters (representing volumetric flux vs pressure) to obtain permeability, Knudsen diffusion and radius, and diffusibility for different soils and porosities | Dusty gas model |
| [Acton et al. (1998)](#_ENREF_6) \*[[35]](#footnote-35) | Full | * - * - * Natural gas | - | * 30 bar, 60 bar, 120 bar * Up to 60 bar * - | Rupture or Puncture | Description of PIPESAFE risk assessment package, which includes various models that are validated and discussed. Among the experiments used for validation and described here are for the:   * *initial stage of an ignited release after a buried pipe rupture:* thermal characteristics, flow rate, pressure, fire geometry, and crater shape and dimensions for different soils (rupture) * *quasi steady-state fire behavior:* thermal characteristics, fire geometry, flow rate (rupture) * *quasi steady-state fire behavior:* thermal characteristics, fire geometry (natural gas puncture) | - |
| [Acton et al. (2000)](#_ENREF_7) | Full | Natural Gas | 1 m | 59 bar | Rupture | Thermal radiation, mass outflow, overpressure, atmospheric conditions, and flame dimensions resulting from release and fire for different crater configuration (naturally occurring crater and predefined crater) | - |
| [Leis et al. (2002)](#_ENREF_50) | Unavailable study reported to perform experimental investigations and suggest correlations by the Batelle Institute | | | - | Rupture | Crater width as function of pipe diameter, depth of cover, qualitative soil description, gas specific heat ratio, gas and soil densities, and critical velocity usually taken as constant | - |
| [Acton and Baldwin (2008)](#_ENREF_5) \*\* | Empirical based on (natural gas) incidents from various databases, including PHMSA[[36]](#footnote-36) | | | - | Rupture | Ignition probability following gas release as function of pipe pressure and pipe diameter (also applicable to punctures with some modifications) | - |
| [Hibi et al. (2009)](#_ENREF_38) | Small | Methane, or carbon dioxide | 0.9 m (column) | ~0.97 bar | Point source of gas (4.3 mm) | Spatial and temporal gas concentration distribution profiles for different gases | Dusty gas model, Fickian diffusion, Blanc’s law |
| [Acton et al. (2010a)](#_ENREF_4) | Full | Hydrogen | 1 m | 60 bar | Rupture | Thermal radiation, mass outflow, overpressure, atmospheric conditions, flame and crater dimensions resulting from release and fire for different soils and wind conditions | - |
| [Acton et al. (2010b)](#_ENREF_8) | Full | Natural gas | 1.2 m | 60 bar, 80 bar | Rupture  Puncture: 25 mm, 80 mm | Heat loading within crater following a rupture  Crater dimensions for different pressures, soil types, pipe and hole diameters  Effect distances as function of pressure, pipe diameter, and soil type | - |
| [Okamoto and Gomi (2011)](#_ENREF_68) | Full | Methane and PA13A (propane air 13A) | 1.2 m | 0.002 bar | Point source of gas | Spatial and temporal gas concentration distribution profiles for different gases | Advective-diffusive model |
| [Hibi and Taguchi (2011)](#_ENREF_40) | Small | Nitrogen, carbon dioxide, or oxygen | 0.9 m | 0 - 0.15 bar | Point source of gas | Spatial and temporal gas concentration distribution profiles for different gases, soil characteristics, and pressure drop to obtain coefficients of dispersivity, molecular diffusion and Knudsen diffusion | Dusty gas model |
| [Hibi et al. (2012)](#_ENREF_39) | Small | Nitrogen, carbon dioxide, or oxygen | 0.9 m | 0 - 0.15 bar | Point source of gas | Spatial and temporal gas concentration distribution profiles for different gases, soil characteristics, and pressure drop to obtain coefficients of dispersivity, molecular diffusion, Knudsen diffusion, and mechanical dispersion | Dusty gas model |
| [Lowesmith and Hankinson (2012)](#_ENREF_60) | Full | Natural gas and natural gas/hydrogen mixtures | Unburied | 60 bar | 20 mm, 35 mm, 50 mm | Thermal radiation, atmospheric conditions, flame dimensions, and heat loads resulting from release and fire for different mass flow rates, wind conditions, hole diameters and gas mixtures | - |
| [Lowesmith and Hankinson (2013)](#_ENREF_59) | Full | Natural gas and natural gas/hydrogen mixtures | 0.2 m (without soil on top – crater not backfilled) | 70 bar | Rupture | Thermal radiation, mass outflow, overpressure, atmospheric conditions, and flame dimensions resulting from release and fire for different gas mixtures and wind conditions | - |
| [Farrag and Wiley (2013)](#_ENREF_34) | Full | Methane | - | 0.017 - 1.380 bar | 1.6 - 3.175 mm | Leak flow rate for different hole diameters, pressures, soil types | - |
| [Luo et al. (2013)](#_ENREF_61) | Small | Compressed air | - | - | Point source of gas (<5 mm) | Pressure drop measurements to obtain high-speed Darcy correction coefficient | Darcy’s law |
| [Lutostansky et al. (2013)](#_ENREF_62) \* | Full | Hydrogen | 1 m | 60 bar | Rupture | Thermal radiation, atmospheric conditions, flame and crater dimensions resulting from release and fire for different wind and soil backfill conditions  Properties are also estimated by PHAST software. The fraction of heat radiated and release angle are suggested as modifications | - |
| [Okamoto et al. (2014)](#_ENREF_69) | Full | Hydrogen | 1.2 m | 0.002 bar | Point source of gas | Spatial and temporal gas concentration distribution profiles for different testbed configurations | Advective-diffusive model |
| [Foissac et al. (2014)](#_ENREF_35) \* | Full | Methane | 0.8 m, 0.6 m | 0.04 - 15 bar | 1 mm, 5 mm | Spatial and temporal gas concentration distribution profiles for different pressures, hole diameters, testbed and soil textural configurations | - |
| [Yan et al. (2015)](#_ENREF_103) | Full | Natural gas (2.5% methane and 97.5% air) | 0.9 m to the pipe centerline | 3 - 24 sL/min | 5 mm | Spatial and temporal gas concentration distribution profiles for different volumetric flow rates (standard), release orientations (& release duration) | - |
| [Acton et al. (2016)](#_ENREF_3) \*\* | Empirical based on (natural gas) incidents from various databases, including PHMSA36 | | | - | Rupture | Ignition probability following gas release as function of pipe pressure and pipe diameter (also applicable to punctures with some modifications) | - |
| [Silva et al. (2016)](#_ENREF_80) \*\* | Empirical based on real accidents from various databases, mostly international regulatory agencies | | | - | Rupture | * Transforming effect distances of [Acton et al. (2010b)](#_ENREF_8) into crater width correlations as function of pressure, pipe diameter, and soil type * Crater width as function of pressure, pipe diameter, depth of cover, gas specific heat ratio, and soil density * Comparison between different empirical models based on an FORTAN code | - |
| [Deepagoda et al. (2016)](#_ENREF_25) \* | Small | Natural gas assumed as methane (5% methane, 95% nitrogen) | 0.33 m | 0.5 L/min | Point source of gas | Spatial gas concentration distribution profiles for different soil textural configurations, soil water saturations, wind velocities, atmospheric temperatures | - |
| [Deepagoda TKK et al. (2018)](#_ENREF_26) \*[[37]](#footnote-37) | Small | Natural gas (5% methane, 95% nitrogen) | 0.33 m | 0.5 L/min | Point source of gas | Spatial gas concentration distribution profiles for different soil textural configurations, soil water saturations, wind velocities, atmospheric temperatures | - |
| [Houssin-Agbomson et al. (2018)](#_ENREF_43) | Full | Methane, hydrogen, nitrogen | 1 m | 17 - 78 bar | 1 - 15 mm but only 12 mm is reported | Regimes for various pipe pressures, release orientations, soil types, gas types | - |
| [Bonnaud et al. (2018)](#_ENREF_13) | Small | Air or nitrogen | Up to 0.18 m | Up to 15 bar | 1.2 mm, 2.2 mm, 2.8 mm | Regimes for various pipe pressures, burial depths, soil types, hole diameters, soil water content, pipe diameters | - |
| [Acton et al. (2018)](#_ENREF_2) \*\* | Empirical work based on previous experimental studies engaging:   1. Full-scale 2. Full-scale 3. Real incidents and/or PIPESAFE | | | - | 1. Rupture 2. Puncture 3. Rupture and puncture | 1. Crater width as function of pressure, pipe diameter, depth of cover, gas specific heat ratio, gas and soil densities, crater profile and critical velocity based on the soil type 2. Use of revised heat fluxes resulting from jet fire punctures of failing pipelines to suggest a less conservative failure probability of the neighboring pipeline 3. Proposition of a probabilistic approach to determine the probability of failure of a pipe following the failure of a neighboring one for different puncture sizes, release orientations, and failure methods | - |
| [Amaya-Gomez et al. (2018)](#_ENREF_10) \*\* | Empirical based on real natural gas accidents using an earlier historical review by the group of [Ramírez-Camacho (2017)](#_ENREF_72) | | | - | Rupture | Probabilistic approach to estimate crater width and depth | - |
| [Ulrich et al. (2019)](#_ENREF_91) | Full | Natural gas (87 ± 2% vol methane) | 0.9 m | 0.52 kg/h, 0.13 kg/h | 6.35 mm | Spatial gas concentration distribution profiles with different wind speeds and ground cover configurations | - |
| [Ramírez-Camacho et al. (2019)](#_ENREF_73) \*\* | Empirical based on real natural gas accidents using various databases including PHMSA36, NTSB[[38]](#footnote-38), etc. | | | - | Rupture | Crater dimensions (length, depth and width) in terms of pipe rupture length, burial depth, pipe diameter |  |
| [Cho et al. (2020)](#_ENREF_20) \* | Full | Methane | 0.91 m | 0.08 - 0.32 kg/h | Point source of gas (6.4 mm) | Spatial and temporal gas concentration distribution profiles for different testbed configurations, flow rates, wind speeds | - |
| [Liu et al. (2021)](#_ENREF_57) \* | Small and Full | Air (Small-scale) and natural gas (full-scale) | 0 - 0.6 m (Small-scale) and 0.8 m (full-scale) | 0 - 0.5 bar (Small-scale)  0 - 5 bar (full-scale) | 1 - 4 mm (Small-scale) and 4 mm (full-scale) | Spatial and temporal gas concentration distribution profiles and volumetric flow rates for different burial depths (small-scale), hole diameters (small-scale), and pressures (small and full-scales) | - |
| [Gao et al. (2021)](#_ENREF_36) \* | Full | Natural gas (85% vol – 95% vol methane) | 0.91 m | 0.5 kg/h, 0.85 kg/h | Point source of gas (6.35 mm) | Spatial and temporal gas concentration distribution profiles for different leak flow rates and soil textural configurations | - |
| [Ren et al. (2022)](#_ENREF_75) \* | Small | Natural gas (4% methane, 96% nitrogen) | 1.2 m | 1 bar | 3 mm | Spatial and temporal gas concentration distribution profiles for different soil temperatures, soil types, testbed and soil textural configurations | - |
| [Tian et al. (2022)](#_ENREF_90) \* | Full | Natural gas (87 ± 2% vol methane) | 0.9 m | 0.08 - 0.52 kg/h | Point source of gas (6.35 mm) | Spatial and temporal surface and above ground gas concentrations for different leak flow rates and atmospheric stability classes  Leak flow rates for different measured and simulated gas concentrations at different atmospheric stability classes and time averaging data by WindTrax model | - |
| [Zhou et al. (2022)](#_ENREF_116) | Small | Propane | 0.075 m | 8.29 – 82.94 m/s | Point source of gas (3.2 mm) | Thermal radiation characteristics, flame dimensions resulting from release and fire for different nozzle velocities (mass flow rates) and pit sizes  Flame area, flame length and flame width as function of HRR[[39]](#footnote-39) (in dimensionless forms)  Radiative fraction as function of Froude number | - |
| [Mbua et al. (2023)](#_ENREF_63) | Full | Natural gas (methane, ethane propane, butane, and air in different proportions) | 0.6 m, 0.9 m, 1.8 m | 1, 5, 10 sL/min | Point source of gas (6.35 mm) | Spatial and temporal methane plume widths, and leak survey speed detection response with different gas compositions (densities), leak flow rates, burial depths | - |
| [Zhu et al. (2023)](#_ENREF_121) | Full | Hydrogen-blended natural gas | 1.4 m | 40 bar, 58 bar | 1 mm | Spatial and temporal gas concentration distribution profiles and leak flow rates with different pressures, hydrogen mixture ratios, leak directions  Gas concentration as function of leak flow rate, leak time, distance from the release, hydrogen mixture ratio  Distance from the release as function of leak flow rate, leak time and hydrogen mixture ratio | - |
| [Jiang et al. (2023)](#_ENREF_47) \* | Full | Methane | 0.9 m | Up to 40 bar | 0.5 mm, 1 mm, 1.5 mm | Spatial and temporal gas concentration distribution profiles and release flow rates with different pressures and hole diameters  Release flow rate as function of pressure and hole diameter  Methane diffusion response time and steady time as function of flow rate at vertical and horizontal diffusion distances | - |
| [Zeng et al. (2023)](#_ENREF_105)[[40]](#footnote-40) \* | Full | Natural gas | 0.1 m | 2 bar | 2 mm | - | - |
| [Jayarathne et al. (2023)](#_ENREF_46) \* | Full | Natural gas (85 -87% vol methane) | 0.9 m | 5 - 21 sL/min | Point source of gas (6.35 mm) | Spatial and temporal gas concentration distribution profiles for different leak flow rates, soil types and testbed and soil textural configurations | - |

\*: also classified as computational

\*\*: only empirical work, no experiments performed

Table A3. Fundamental studies based on the adopted models.

|  |  |  |
| --- | --- | --- |
| **Fundamental model** | **References** | **Also engages experimental work** |
| Fickian diffusion (in porous media) | [Wakoh and Hirano (1991)](#_ENREF_92), [Sleep (1998)](#_ENREF_83), [Hibi et al. (2009)](#_ENREF_38), [Cheng (2014)](#_ENREF_19) | [Wakoh and Hirano (1991)](#_ENREF_92) |
| Advective-diffusive model | ([Sleep and Sykes, 1993](#_ENREF_84)), [Webb and Pruess (2003)](#_ENREF_99), [Okamoto and Gomi (2011)](#_ENREF_68), [Okamoto et al. (2014)](#_ENREF_69), [Parvini and Gharagouzlou (2015)](#_ENREF_71), | [Okamoto and Gomi (2011)](#_ENREF_68), [Okamoto et al. (2014)](#_ENREF_69) |
| Dusty gas model | [Abu‐El‐Sha'r and Abriola (1997)](#_ENREF_1), [Sleep (1998)](#_ENREF_83), [Webb and Pruess (2003)](#_ENREF_99), [Hibi et al. (2009)](#_ENREF_38), [Hibi and Taguchi (2011)](#_ENREF_40), [Hibi et al. (2012)](#_ENREF_39) | [Abu‐El‐Sha'r and Abriola (1997)](#_ENREF_1), [Hibi and Taguchi (2011)](#_ENREF_40), [Hibi et al. (2012)](#_ENREF_39) |
| Blanc’s law | [Hibi et al. (2009)](#_ENREF_38) | [Hibi et al. (2009)](#_ENREF_38) |
| Darcy’s law | [Luo et al. (2013)](#_ENREF_61), [Eparu et al. (2014)](#_ENREF_30) | [Luo et al. (2013)](#_ENREF_61) |
| Non-adiabatic isentropic pipeline leakage model integrated in the energy equation | [Wang et al. (2023b)](#_ENREF_96) | - |
| Simple monopole model | [Hoff (1983)](#_ENREF_41) | [Hoff (1983)](#_ENREF_41) |
| Transient fire model following a rupture (crater source, fluid flow and combustion stalk, cap and radiation submodels) | [Cleaver and Halford (2015)](#_ENREF_22) | - |
| Fire model following a rupture (crater source, fluid flow, combustion, and radiation submodels) | [Cleaver et al. (2001)](#_ENREF_21)[[41]](#footnote-41) | - |

Table A4. Fluidization phenomena studies categorized by soil modelling and work classification.

|  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Fluidization mode** | | **Particle-particle modelling** | | | | **Work classification** | | | | **Measurements Techniques** |
| **Study** | Fluidization | Spout-fluidization | TFM-KTGF | Hard sphere | Soft sphere | NA | Fund./Theor. | Comp. | Exp. | Review/Book | IF Experimental |
| [Massimilla et al., 1963](#_ENREF_66) | ⁕ |  |  |  |  | ⁕ |  |  | ⁕ |  | Pressure measurements using a manometer, weight, volume rate measurements by collection over time |
| [Shi et al., 1984](#_ENREF_86) | ⁕ |  |  |  |  | ⁕ | ⁕ |  | ⁕ |  | Pressure drop measurements using a piezometer, flow measurements using a rotameter, visual observations |
| [Peng and Fan, 1997](#_ENREF_80) | ⁕ |  |  |  |  | ⁕ | ⁕ |  | ⁕ |  | Pressure drop measurements using pressure difference sensor and transducer indicator, flow measurements using a rotameter, visual observations |
| [Niven and Khalili, 1998](#_ENREF_74) | ⁕ |  |  |  |  | ⁕ |  |  | ⁕ |  | Flow measurements using a rotameter, visual observations, fluidization extent (representative geometry like depths and diameters) using probes |
| [Niven, 2002](#_ENREF_73) | ⁕ |  |  |  |  | ⁕ | ⁕ |  |  |  | NA |
| [Link et al. (2004)](#_ENREF_56) |  | ⁕ |  | ⁕ |  |  |  | ⁕ | ⁕ |  | Particle image velocimetry, digital camera |
| [Link et al. (2005)](#_ENREF_52) |  | ⁕ |  | ⁕ |  |  |  | ⁕ | ⁕ |  | High frequency analysis of pressure drop fluctuations, digital camera, visual observations |
| [Zhong et al. (2006)](#_ENREF_114) |  | ⁕ |  |  |  | ⁕ |  |  | ⁕ |  | Multi-channel differential pressure signal system for pressure drop fluctuations, digital camera |
| [Link et al. (2007)](#_ENREF_54) |  | ⁕ |  | ⁕ |  |  |  | ⁕ |  |  | NA |
| [Zhong et al. (2007)](#_ENREF_115) |  | ⁕ | ⁕ |  |  |  |  | ⁕ |  |  | NA |
| [Link et al. (2008)](#_ENREF_53) |  | ⁕ |  | ⁕ |  |  |  | ⁕ | ⁕ |  | Positron emission particle tracking, high frequency analysis of pressure drop fluctuations, visual observations |
| [Link et al. (2009)](#_ENREF_55) |  | ⁕ |  | ⁕ |  |  |  | ⁕ | ⁕ |  | Fiber optics |
| [Epstein and Grace (2010)](#_ENREF_32) |  | ⁕ |  |  |  | ⁕ |  |  |  | ⁕ | NA |
| [Ren et al. (2011)](#_ENREF_74) |  | ⁕ |  |  | ⁕ |  |  | ⁕ |  |  | NA |
| [Nagashima et al. (2011)](#_ENREF_66) |  | ⁕ |  |  |  |  |  |  | ⁕ |  | Analysis of pressure drop fluctuations using pressure transducers, visual observations |
| [Sutkar et al. (2013)](#_ENREF_88) |  | ⁕ |  |  |  | ⁕ |  |  |  | ⁕ | NA |
| [Shao et al. (2013)](#_ENREF_78) |  | ⁕ |  |  |  | ⁕ |  |  |  | ⁕ | NA |
| [van Zyl et al., 2013](#_ENREF_98) | ⁕ |  |  |  |  | ⁕ |  |  | ⁕ |  | Extent of fluidization using scale measurements, pressure measurements using sight tubes, flow measurements using electromagnetic flowmeter |
| [Yang et al. (2014)](#_ENREF_104) |  | ⁕ |  |  | ⁕ |  |  | ⁕ |  |  | NA |
| [Alsaydalani and Clayton (2014)](#_ENREF_9) | ⁕ |  |  |  |  | ⁕ |  |  | ⁕ |  | Particle image velocimetry, digital camera, pressure measurements using pressure transducers and sight tubes, volume rate measurements by collection over time |
| [Epstein (2020)](#_ENREF_31) |  | ⁕ |  |  |  | ⁕ |  |  |  | ⁕ | NA |
| [Zhao et al. (2021a)](#_ENREF_111)1 | ⁕ |  |  |  |  | ⁕ |  |  | ⁕ |  | Light and digital camera |
| [Zhao et al. (2021b)](#_ENREF_112) |  | ⁕ | ⁕ |  |  |  |  | ⁕ |  |  | NA |
| [Esgandari et al. (2023)](#_ENREF_33) |  | ⁕ | ⁕ |  | ⁕ |  |  | ⁕ |  |  | NA |
| [Hoorijani et al. (2024)](#_ENREF_42) |  | ⁕ |  |  | ⁕ |  |  | ⁕ |  |  | NA |

Table A5. Detection techniques studies categorized by method and work classification.

|  | **Detection method** | | | | | | | **Work classification** | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Detection study** | Airborne | Acoustic | Temperature | Resistivity | Model-based | Accelerometer | Probabilistic Neural Network | Fund./Theor. | Comp. | Exp. |
| [Botros et al. (2008)](#_ENREF_14) | • |  |  |  | • |  |  | • |  |  |
| [Li and Li (2009)](#_ENREF_51) | • |  |  |  |  |  |  |  | • | • |
| [Kim and Lee (2009)](#_ENREF_49) |  | • |  |  |  |  |  | • | • | • |
| [Jiao et al. (2009)](#_ENREF_48) |  | • |  |  |  |  |  |  |  | • |
| [Ozevin and Harding (2012)](#_ENREF_70) |  | • |  |  |  |  |  |  |  | • |
| [Inaudi et al. (2012)](#_ENREF_45) |  |  | • |  |  |  |  |  |  | • |
| [Xu et al. (2016)](#_ENREF_102) |  | • |  |  |  |  |  |  |  | • |
| [Lopezlena and Sadovnychiy (2019)](#_ENREF_58) |  |  |  |  | • |  |  | • |  | • |
| [Zhou et al. (2019)](#_ENREF_119) |  |  | • |  |  |  |  |  | • | • |
| [Zhou et al. (2020a)](#_ENREF_118) |  |  | • |  |  |  |  |  | • | • |
| [Zhou et al. (2020b)](#_ENREF_120) |  |  | • |  |  |  |  |  | • | • |
| [Zhang et al. (2020)](#_ENREF_109) |  |  |  |  | • |  |  | • |  |  |
| [Muggleton et al. (2020)](#_ENREF_65) |  | • |  |  |  |  |  |  |  | • |
| [Wang et al. (2021a)](#_ENREF_93) |  | • |  |  |  |  |  |  | • |  |
| [Wang et al. (2021b)](#_ENREF_97) |  |  |  |  | • |  |  |  | • |  |
| [Bu et al. (2021a)](#_ENREF_16) |  |  |  |  | • |  |  |  | • |  |
| [Bu et al. (2021b)](#_ENREF_17) |  |  |  |  | • |  |  |  | • |  |
| [Zhang et al. (2021a)](#_ENREF_106) |  | • |  |  |  |  |  |  | • | • |
| [Xiao et al. (2021)](#_ENREF_101) |  | • |  |  |  | • |  |  |  | • |
| [Sun et al. (2021)](#_ENREF_87) |  |  |  | • |  |  |  |  | • | • |
| [Zhang et al. (2022)](#_ENREF_110) |  | • |  |  |  |  |  |  |  | • |
| [Tan et al. (2023)](#_ENREF_89) |  |  |  |  |  |  | • |  | • | • |

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1. Pressure is reported in gauge [↑](#footnote-ref-1)
2. The gas released was 5% methane 95% nitrogen [↑](#footnote-ref-2)
3. The study didn’t mention performing validation, however, the authors built on the model suggested by [Silva et al. (2017b)](#_ENREF_82) and validated by [Lowesmith and Hankinson (2013)](#_ENREF_59) [↑](#footnote-ref-3)
4. Consequence distance: diameter of the biggest cross section of the consequence region (area of 5% concentration) [↑](#footnote-ref-4)
5. The gas released was natural gas considered as a mixture of methane, ethane, and propane [↑](#footnote-ref-5)
6. The gas released was air [↑](#footnote-ref-6)
7. Risk area: soil area where natural gas concentration is higher than 0.0283 (corresponding to LEL of 5% vol) [↑](#footnote-ref-7)
8. Safety distance: distance where gas concentration reaches 5% by volume [↑](#footnote-ref-8)
9. Alarm time: time when gas concentration reaches 5% by volume [↑](#footnote-ref-9)
10. First dangerous time (FDT): time when methane crosses to the atmosphere (reference is LEL of methane 5%) [↑](#footnote-ref-10)
11. Farthest dangerous range (FDR): longest lateral diffusion distance attained by methane in soil (reference is LEL of methane 5%) [↑](#footnote-ref-11)
12. Ground dangerous range (GDR): range of methane on the ground upon achieving FDT (reference is LEL of methane 5%) [↑](#footnote-ref-12)
13. Methane invasion distance (MID): Furthest horizontal diffusion distance on the ground within a methane volume of 5% [↑](#footnote-ref-13)
14. Methane invasion limit state (MILS): time at which the gas attains its stable MID (see footnote 13) [↑](#footnote-ref-14)
15. Methane invasion limit distance (MILD): distance achieved at MILS [↑](#footnote-ref-15)
16. The numerical model they used is previously validated by [Deepagoda et al. (2016)](#_ENREF_25) and [Cho et al. (2020)](#_ENREF_20) experiments [↑](#footnote-ref-16)
17. They used a similar model to [Deepagoda et al. (2016)](#_ENREF_25), while accounting for the wind effect [↑](#footnote-ref-17)
18. The numerical model they used is previously validated by [Deepagoda et al. (2016)](#_ENREF_25) and [Cho et al. (2020)](#_ENREF_20) experiments [↑](#footnote-ref-18)
19. The gas released was sour natural gas considered as a mixture of methane, ethane, propane, nitrogen, carbon dioxide and hydrogen sulfide [↑](#footnote-ref-19)
20. First Dangerous Zone (FDZ): cavity zone of the building where the leakage is occurring, classified as a high-risk zone [↑](#footnote-ref-20)
21. Second Dangerous Zone (SDZ): cavity zone adjacent to the one corresponding to FDZ in the downwind direction, also expected to be a high-risk zone [↑](#footnote-ref-21)
22. Underground adjacent confined space hazardous boundary: minimum distance between the release hole and center of the confined adjacent space corresponding to a maximum gas concentration of 5% (LEL of methane) [↑](#footnote-ref-22)
23. Dangerous radius: contour radius corresponding to a concentration of 5% (LEL of methane) [↑](#footnote-ref-23)
24. Box culvert: box reinforced with concrete around the pipe where the release occurs, filled with soil, and surrounded by a loamy bed of soil [↑](#footnote-ref-24)
25. First Hazardous Time (FHT): time required for the released gas to reach the ground surface [↑](#footnote-ref-25)
26. Fastest Hazard Distance (FHD): maximum horizontal extent of diffusion corresponding to the hazardous area (where gas concentration exceeds LEL of 5%) [↑](#footnote-ref-26)
27. Lateral Hazardous Distance (LHD): maximum lateral extent of diffusion corresponding to the hazardous area (where gas concentration exceeds LEL of 5%) in the loamy soil [↑](#footnote-ref-27)
28. The gas released was hydrogen-enriched natural gas [↑](#footnote-ref-28)
29. The gas released was hydrogen [↑](#footnote-ref-29)
30. The gas released was hydrogen-blended natural gas [↑](#footnote-ref-30)
31. The experimental portion of this study proposed flow rate (and response and steady times) empirical correlations and investigated the effect of some properties on the release [↑](#footnote-ref-31)
32. Explosive range volume: volume of natural gas above the soil layer, in the tunnel space region, within the explosive range (5% - 15%) [↑](#footnote-ref-32)
33. The numerical model they used is previously validated by [Deepagoda et al. (2016)](#_ENREF_25) and [Cho et al. (2020)](#_ENREF_20) experiments [↑](#footnote-ref-33)
34. Aim was to measure properties; not perform leak experiments [↑](#footnote-ref-34)
35. Elaborates on the computational software (PIPESAFE); includes description of mathematical models validated by experiments, empirical models based on experiments, in addition to the discussion of some of the experiments [↑](#footnote-ref-35)
36. PHMSA: Pipeline and Hazardous Materials Safety Administration [↑](#footnote-ref-36)
37. Their computational domain didn’t include soil modelling [↑](#footnote-ref-37)
38. NTSB: National Transportation Safety Board [↑](#footnote-ref-38)
39. Heat release rate (HRR): correlates nozzle velocity and jet impinging wall area. Dimensionless HRR couples flame area to different geometrical pits [↑](#footnote-ref-39)
40. The computational portion of this study investigated the effect of various properties on the release and performed a grey correlational analysis. The experimental work was for validation of the suggested model. [↑](#footnote-ref-40)
41. Employed the work of [Acton et al. (2000)](#_ENREF_7) to validate their fundamental model [↑](#footnote-ref-41)