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Understanding Mid-to Large Underground Leaks from Buried Pipelines as Affected by Soil and Atmospheric Conditions – Field Scale Experimental Study

PRCI-REX2022-020

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Abstract

Reducing the amount of leaked natural gas (NG) from pipelines from production to use has become a high priority in efforts to cut anthropogenic emissions of methane and ensure public safety. However, tracking and evaluating NG pipeline leaks, especially at moderate to high flow rates, requires a better understanding of the leak from the source to the detector as well as more robust quantification methods. To better understand fugitive emissions from NG pipelines, we developed a field scale testbed that simulates mid and high-pressure gas leaks from belowground natural gas infrastructure. The system is equipped with subsurface, surface and atmospheric sensors to continuously monitor changes in soil and atmospheric conditions (e.g., moisture, pressure, temperature) and methane concentrations near real-time throughout the site. Using this testbed, we are currently conducting a series of gas leakage experiments to study the transient behavior of significant pipeline leaks subjected to varying subsurface (e.g., soil moisture, heterogeneity, competing utilities) and atmospheric conditions (near-surface wind and temperature). This work has also led to the advancement of methods for measuring underground gas concentration for high-speed migration during transient leakage events. Our approach allows us to establish the relative importance of the many pathways for methane migration between the source and the sensor location. These findings will better inform leak detectors of leak severity, aiding with safety precautions and work order categorization for improved efficiency.

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Introduction

With the increased use of natural gas (NG) as a transition fuel on the path towards low-carbon energy, safety and environmental concerns from leaking underground natural gas pipelines are widespread. For example, in 2020 alone, there were approximately 630,000 leaks in U.S. distribution mains (Weller et al., 2020). Underground NG leaks, especially at moderate to high flow rates, can result in gas migration and buildup producing explosive concentrations (5% v/v of methane) within nearby structures (basements, foundations, or sewers). A critical knowledge gap is how environmental conditions effect gas migration behavior in these scenarios and how to properly account for this behavior in decision making.

Although recent technology advances in methane detection have improved above-ground leak detection and repair (LDAR) accuracy and efficiency, these improvements do not readily transfer to subsurface leaks from pipelines due to the complex behavior of subsurface gas migration and diffuse surface presentation of underground leaks. Large leaks behave differently during the critical transient phase immediately after leak initiation and depending on the leak size. Leaks generally range in size from small (0-2.2 splm (0-4.7 SCFH), medium (2.2-35.4 slpm (4.7 – 75 SCFH)), and large (>35.4 slpm (75 SCFH +)) (Hendrick et al., 2016; Lamb et al., 2015; Weller et al., 2018). For example, Gao et al., 2020 shows how medium to high leak rates can cause faster and farther migration of NG due to the dominant effect of the advective, pressure driven flow near the leak location. Fate and transport of the leaked gas within the subsurface is primarily controlled by soil layers, subsurface infrastructure, pipeline pressure and gas composition. Surface conditions such as pavement, frost or structures create barriers to gas flow and release to the atmosphere, increasing lateral transport or causing gas accumulation below ground. Environmental conditions such as near-surface wind, barometric pressure, temperature, and precipitation further affect the gas behavior and oftentimes subsurface accumulation of the gas plumes (Poulsen et al., 2003; Oertel et al., 2016: Forde et al., 2019; Bahlmann et al., 2020; Page et al. 2021).

The combination of faster movement and potential accumulation factors such as gas migration into structures (basements, foundations, or sewers) and thereby buildup of explosive limits (5% v/v of methane) present a unique hazard situation. Inadequate understanding of the combined effects of the subsurface gas transport and atmospheric formation of NG plumes under different factors, i.e, combination of leak -subsurface-structural-atmospheric characteristics, increase the potential risks to end users and first responders during a leak response incident. However, better understanding of the conditions that impact gas migration distance and speed will support a more efficient response to leaks in general, and ultimately allow operators and first responders to quickly identify scenarios where gas may migrate extended distances.

To create a more complete picture of NG leak behavior, we developed a field scale experimental testbed and related experimental methods to properly measure and understand the subsurface and atmospheric transient behavior of pipeline leaks and thereby to characterize them based on controlling parameters and the leak properties. The testbed and novel methods allow us to make direct measurements of gas migration speed and extent in the subsurface, surface and atmosphere in a range of environmental conditions. This is further extended by pairing measurements with models to extend knowledge beyond measured scenarios not accessible in the field. The following sections and referenced supporting documents (Jayarathne et al., 2022) outline our experimental approach and new measurement techniques.

Background

As distribution networks carry NG in populated areas, leaks have the potential to present health and safety risks when they migrate through the soil and accumulate in enclosed spaces such as foundations, basements, storm drains, or utility conduits. Over the last decade, 1,199 subsurface pipeline gas leaks in the US were reported resulting 39 deaths and 281 injuries that required in -patient hospitalizations (PHMSA, 2019). Of these fatalities, 64% were members of the general public and the result of explosions caused by leaks in the distribution network. Distribution networks typically carry NG at pressures from 1.5 - 2000 kPa (Chamindu Deepagoda et al., 2016) in plastic, steel and cast iron pipes. Pipes are located at depths of 0.05 to 1.5 m below the surface (PHMSA, 2019) from the city gates to residential and end users (Table 1).

Table 1: Details of explosive events as presented in the PHMSA incident reports (PHMSA, 2019).

Tm(mins)	D_p (cm)	T (°C)	WS (m/s)	D_{ex} (m)	Hole (cm)	P_p (kPa)	Cover	Sub	Found
203	91	1	0	15	Crack	131	G/C	S	S
126	91	28	2	20	Crack	372	G/C	S	B
73	76	-6	0	5	Crack	103	C	S	B
67	97	-1	8	20	5	172	A	U	B
67	94	2	5	5	Crack	124	A	U	S
52	119	-1	5	10	5	414	A/C/G	S	B
31	46	17	5	10	2.5	400	A/C	U	B
30	152	6	3	5	15	152	G	R	C
0	137	35	3	25	Crack	101	G/C	S	C
0	109	25	4	15	Crack	345	G	S	S
0	81	-3	6	5	Crack	124	A/C	U	B

Tm – time between the emergency services being informed of the leak and the explosion occurring
D_p – depth of leak
D_{ex} – Distance from leak to explosion
T- air temperature
WS – Wind Speed
Hole – the size of the hole in pipeline
P_p – backing pressure of the gas in the pipeline
Cover – land type cover (*G*-Grass, *C*-Concrete, *A*-Asphalt)
Sub – subsurface complexity (*R*-Rural, *S*-Suburban, *U*-Urban)
Found – Foundation of the structure (*B*-Basement, *S*-Concrete Slab, *C*- Crawlspace or piers

Data from the Pipeline and Hazardous Materials Safety Administration (PHMSA) "Pipeline Incident Flagged Files" show that the biggest cause of fatality in the general public (90% of incidents) occurred when their dwelling exploded (Table 1). An explosion will occur when NG migrates from a leak to a confined space and builds up explosive concentrations. Three events in PHMSA-flagged files happened before emergency responders were alerted to the gas leak, while further explosions happened between 30 and 203 minutes after the leak had been initially reported. This gives a clear understanding that first responders lack sufficient information on NG transport to effectively identify which dwellings are at the greatest risk.

As there are many variables that can affect the speed of NG flow (environmental conditions, soil moisture, gas pressure, other underground infrastructure, surface covering, rural/urban/suburban environments) and gas infiltration into structures (foundation types) there are too few incidents to statistically evaluate the circumstances that will increase the distance NG will travel. Several studies have investigated gas flow through soil experimentally (e.g., Chamindu Deepagoda et al., 2016; Cho et al., 2020), as a combination of experiments and simulations (Okamoto and Gomi, 2015; Gao et al., 2021), with the key points detailed in Jayarathne et al., 2022, but these studies focus mainly on select environmental conditions for small leak rates, mostly under controlled environmental conditions. In addition, none of the abovementioned studies focus on the effect of surface cover and underground infrastructure on gas transport.

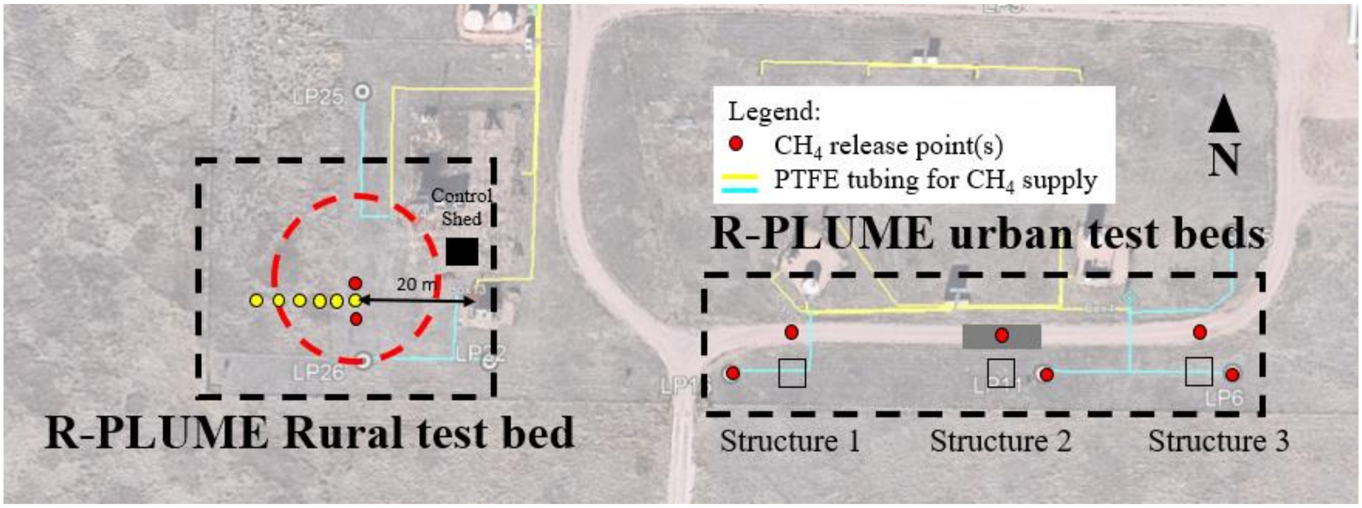

Figure 1:Rural (designed to understand transient behavior of NG emissions) and Urban testbeds (Structure 1 with a Crawlspace, Structure 2 with a basement, and Structure 3 with a Concrete slab) designed and built at Colorado State University's Methane Emission Technology Evaluation Center (METEC).

To address these abovementioned shortcomings, two testbeds were designed and built at Colorado State University's Methane Emission Technology Evaluation Center (METEC) in Fort Collins, CO. The testbeds allow for the simulation of underground pipeline leaks at known leakage rates in varying subsurface and surface conditions, allowing for both control and measurement of subsurface and surface conditions on a continuous basis. A "rural" testbed was designed to investigate gas transport from gathering and transportation pipelines, representing a rural environment with undisturbed soil. The "urban" testbed was designed to test how NG will travel in urban and suburban environments, represented by complex infrastructure. A suburban environment is simulated using impermeable coverings (roads/driveways), semipermeable covering (gardens) and closed subsurface conduits (representing sewage and telecommunication pipe). The urban environment is simulated using selectively open conduits (older/doused pipework) and impermeable coverings (roads). The testbeds are instrumented with a variety of subsurface, surface and atmospheric sensors to continuously monitor the gas and environmental conditions throughout the site at high temporal and spatial resolutions. The next section and support information (Jayarathne et al., 2022) provides details of the test bed design, sensor instrumentation and testing as well as offers some sample experimental data.

Methods

Rural testbed design and instrumentation

A view of the rural test bed can be seen in Figure (2). In general, the test bed consists of emission points located at two depths belowground (0.9m and 1.8m) and over 70 belowground, surface and atmospheric sensors to capture both the gas concentration and environmental conditions. Gas is supplied by 0.635 cm PTFE tubing and released via a 0.635 cm vent screen (model SS-MD-4, Swagelok, USA) surrounded by a 10cm wire cube filled with gravel to prevent clogging. Compressed NG with methane compositions ranging from 85%vol – 95%vol methane are provided from two 145 L cylinders and controlled using pressure regulation and solenoid valves in series with precision orifices. Each emission point is capable of releasing between 10 and 300slpm. All subsurface methane concentrations in the rural testbed were continuously measured at 30 belowground locations (Figure 2) using custom designed SGX INIR-ME 100% sensors (SGX, Katowice, Poland). While methods for measuring steady state underground gas concentrations are well developed (Ulrich et al., 2020), methods to measure high speed migration during transient events were developed specifically for the rural and urban test beds. The sensors have a realistic detection limit of 300ppm, can measure up to 100% and were configured to measure CH_4 concentrations at 0.9m, 0.6m and 0.3m below the surface at distances 0.9m, 1.8m 3m, 4.5m, 15m, and 30m from the leak point as shown in Figure (2). Details of the controlled release procedure, sensor selections, calibration, installation, standard operation procedure and data analysis are presented in the supplementary material in Jayarathne et al. (2022).

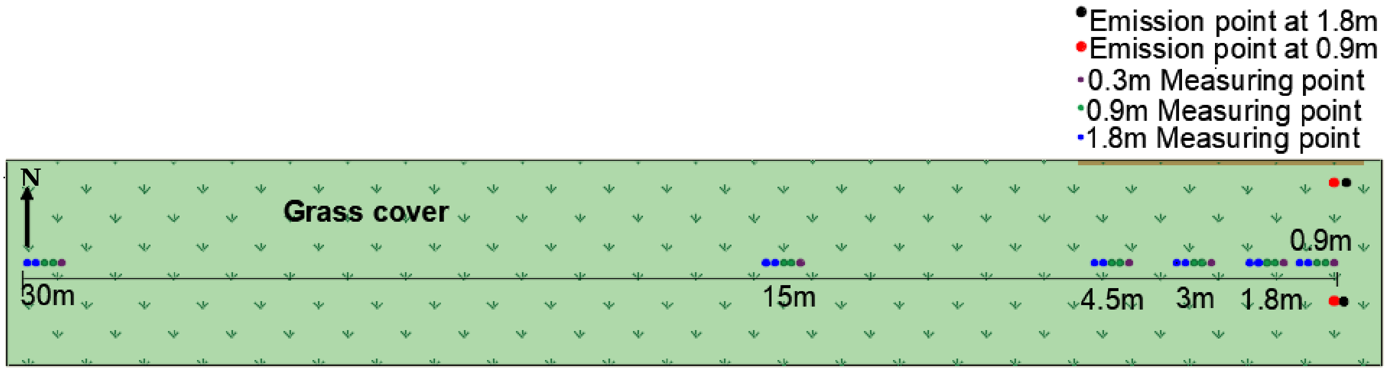

Figure 2: Plan view of the "Rural" testbed designed to investigate the transient behavior of underground NG releases that travel though undisturbed soil under different environmental conditions. The locations of the belowground sensors with respect to release points are shown.

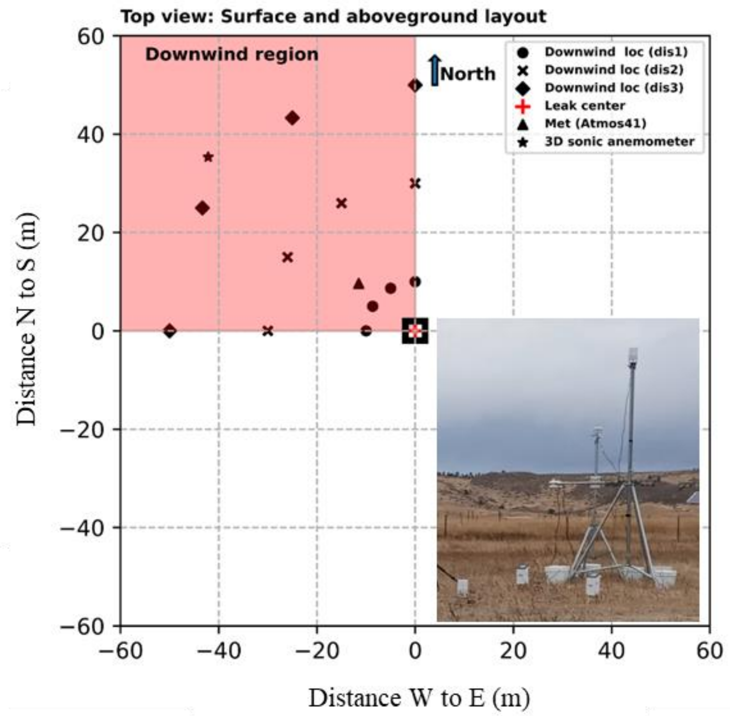

Figure 3: Plan view of identified downwind locations for atmospheric CH_4 measurements and positioning of the ATMOS41 weather stations for meteorological measurements.

In addition to methane measurements, a network of 39 sensors was installed within the testbed to monitor soil moisture, matric potential and temperature. Soil moisture was monitored using the TERROS10 (METER Group, Inc.; USA), combined moisture and temperature using TERROS11 (Decagon Devices, Inc.; USA), and matric potential and temperature using TERROS21 (METER Group, Inc.; USA) sensors. Above the surface, weather stations (ATMOS 41, METER Group, Inc.; USA) were installed at 12+ locations collocated with various trace gas analyzers to measure the wind speed, air temperature, wind direction and precipitation at two heights of 0.05m, 3.0m. Additionally, data from the METEC MET station positioned at 6m AGS (3D 81000V Ultrasonic Anemometer, R.M.Young Company, USA) were also collected. Continuous recording of data was enabled using ZL6 data loggers (METER Group, Inc.; USA) for data storage with data recording span of 30 seconds. A sample layout of the weather stations is seen in Figure (3).

Urban Testbed design and instrumentation

The urban test bed consists of three test locations with structures simulating houses that vary depending on foundation type – basement, crawlspace and slab. The foundation footprints are 1.8m x 1.8m to match the footprint of three wooden sheds, similar to a garden shed, placed on top of each of the foundations. Figure (4) shows the schematic of one of the three structures/foundations installed at the urban test bed. All three structures are aligned 3.5m south from the road running in the East-West direction. Structure spacing was determined to avoid any potential interference with NG releases from other structures. Each structure has two NG release points located 0.9m below ground surface (BGS), and 5.5m away from the edge of the foundation (Figure 1) with a release capability of 10 to 300slpm. Depths were selected based on soil cover requirements for NG distribution mains which ranges from 24 to 48 inches, depending on the type, class and location of the pipeline (Electronic Code of Federal Regulations §192.327 Cover, 2021).

Gas supply for the underground releases follow the same procedure as the “rural” testbed. Importantly, determination of subsurface methane concentrations is performed in two ways. Methane concentration is measured 0.9m, 0.6m, and 0.3m BGS (Figure 4), using SGX INIR-ME 100% sensors similar to the rural testbed. An additional set of belowground measurements were conducted near the soil surface (0.1m BGS) based on knowledge of the oxygen concentration using a method previously tested by Bahlmann et al., 2020 and further validated here (Jayarathne et al., 2022). Sensors (Figaro KE25 series, Figaro Inc. USA) were buried in the soil and interfaced with continuous data acquisition using CR1000 data loggers (Campbell Scientific, Inc.; USA). The calculation of methane concentration using the measured oxygen readings was based on the method adopted by Bahlmann et al. (2020). Surface methane concentrations were measured using natural gas detectors developed in Cho et al. (2022), consisting of metal oxide semiconductor sensors (TGS2611-EOO, Figaro USA Inc), combined with sensors for relative humidity, temperature and absolute pressure measurements. Further details on sensor assembly, calibration, and field performance can be found at Cho et al. (2022) while the adaptation for the urban testbed is presented in the supplementary material in Jayarathne et al. (2022). Measurement methods for meteorological data were similar to the rural testbed with three weather station sensors located at 0.05 m, 0.5 m, and 1 m above the surface.

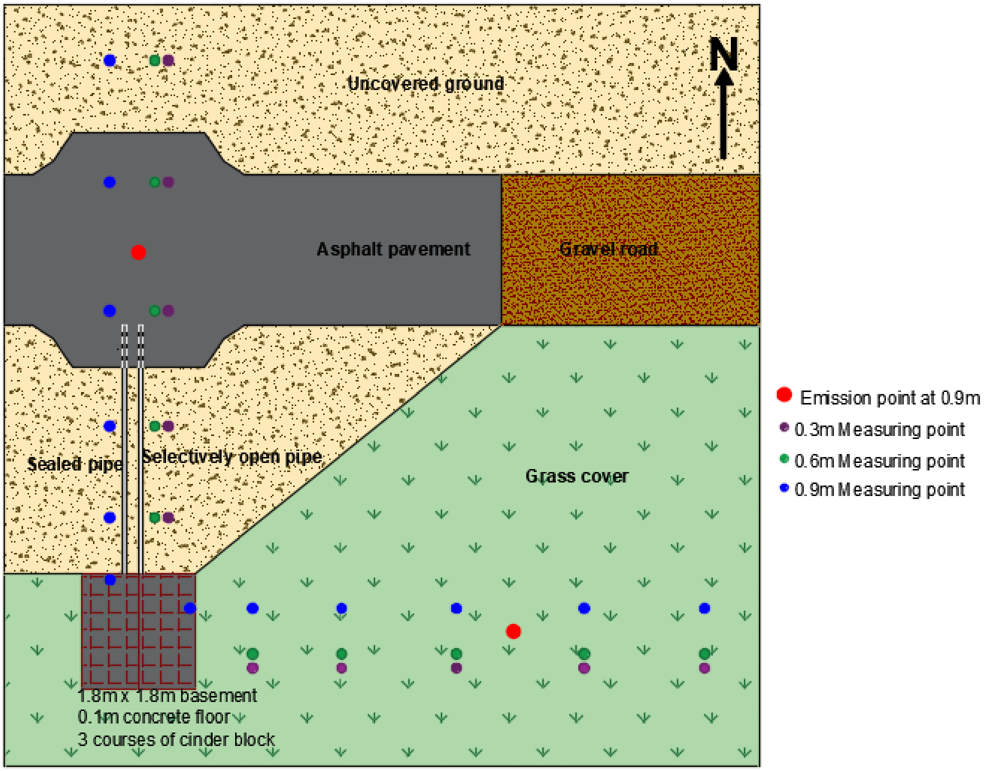

Figure 4: Plan view of one of the three structures (basement) of the urban testbed designed to investigate the NG migration in urban and suburban environments. The other two structures share the same design, varying only with the type of foundation (Concrete slab, Crawlspace)

Experimental methods

Experiments varied in terms of the leak rate and location/depth, soil moisture conditions, surface treatment and building foundation. Table (2) shows a brief summary of the experimental conditions tested. For the sample experimental data shown below, the leak rates were 10-50 slpm with an additional 2 slpm proof-of-concept experiment. The 10- 50 slpm leaks represent a range of mid to large leaks (> 2.2 slpm) while the 2slpm was selected to represent a NG leak that would potentially be seen during a walking survey. Each experiment was initiated by regulating the gas pressure and opening the solenoid value to achieve the desired leak rate. Soil moisture, temp and matric potential was measured every 10 minutes. Gas concentration within the soil profile and on the soil surface was measured/calculated every 5 seconds. Each experiment ran for a total of 24 hrs based on the experimental goals specific to this data set. For future experiments, should there be interest in the impact of a slow leak in the presence of a water infiltration front over time, an experiment may run for 2-3 weeks. In the event of a high leak rate and an open conduit, experiments may last for a total of 2-4 hours.

Table 2: Experimental conditions tested.

Textural configuration	**Leak Rate SCFH (SLPM)**	**NG composition**	**Average Moisture Saturation**	**Structure Foundation**	**Surface Treatment**	**Average Weather Conditions**
- Disturbed trenched soil - Undisturbed soil - Competing utilities, open/closed pipe (preferential pathway for gas flow)	4.24, 21.8 – 106 SCFH (2, 10-50 SLPM)	Gaseous mixes of Methane, Ethane, Propane and Butane as required	25% - 40%	- Basement - Concrete slab - Crawlspace	- Natural vegetation - Pavement - Artificial turf - Snow - Ice	Varies - Wind: ~0.5 – 6 m/s - Temperature: -14 -30 ℃ - Precipitation: 0 to 7cm/ day

Results and Discussion

Proof of Concept of developed experimental methods

Shown below are results from two sets of Proof-of-Concept experiments conducted at METEC. Experiments were selected to cover a range of parameters responsible for enhancing subsurface and atmospheric NG migrations.

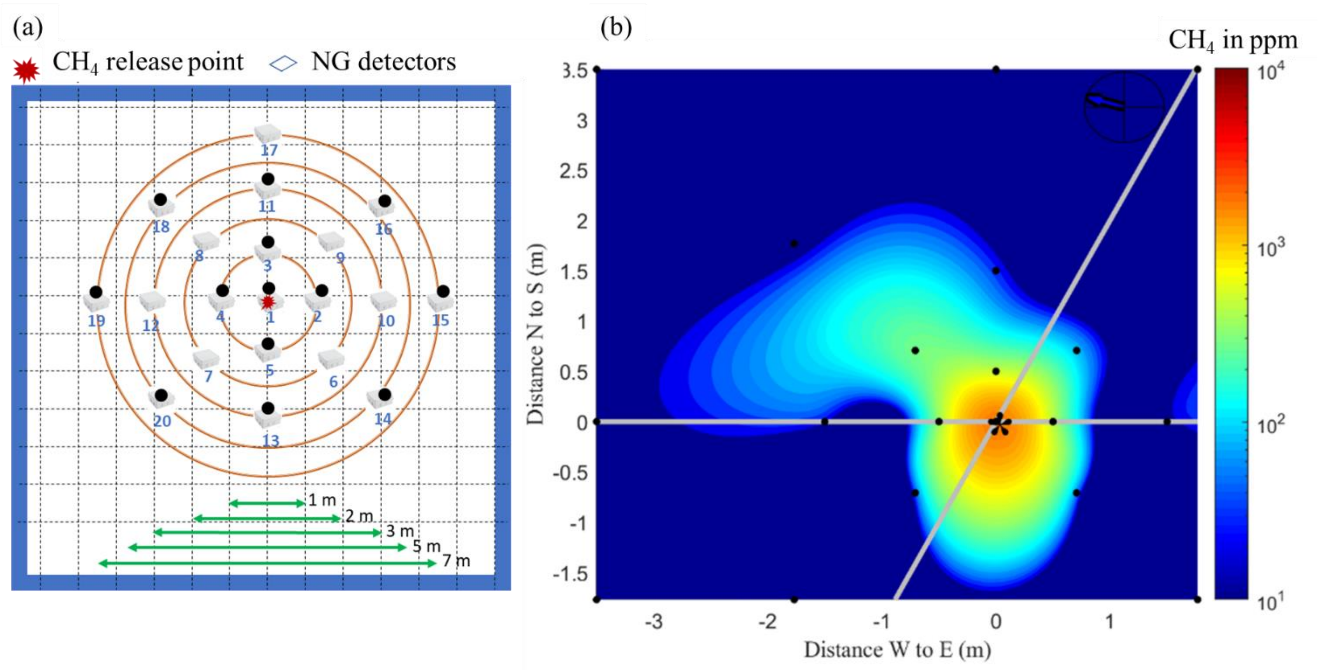

Figure 5: (a) Sample layout of CH_4 detectors located on the soil surface around a hypothetical NG emission point and (b) plot of the surface plume interpolated using the measurements from the CH_4 detectors. White lines show the orientation of belowground utility pipelines installed in the testbed.

During this proof-of-concept experiment (Figure 5), surface and subsurface sensors collected data continuously enabling the understanding of any change in leak behavior and surface plume formation over time. Data collected using the detectors were subjected to data interpolation to generate both the surface an subsurface CH_4 plumes. For this experiment, CH_4 detectors were evenly distributed at the testbed (Figure 5a). Over time, the sensors are capable of capturing any change to the CH_4 plume (Figure 5b). In this specific case, the subsurface heterogeneity added complexity to the pipeline scenario, resulting in the asymmetrical CH_4 distribution.

Shown in Figure (6) are results of a test conducted to understand the transient behaviour of NG leaks in urban and suburban environments. The vertical plume sections were generated by interpolating the continous measurements taken from the INIR sensors. All plots are shown at 6 hrs after the start of 10 slpm and 50 slpm gas releases, for comparision. The plots clearly show how different plume patterns result from varying soil, surface cover, and subsurface complexities. Although a small comparision, the experiment helps to confirm the testbed capablity in simulating different susbsurface complexities of urban and suburban environments.

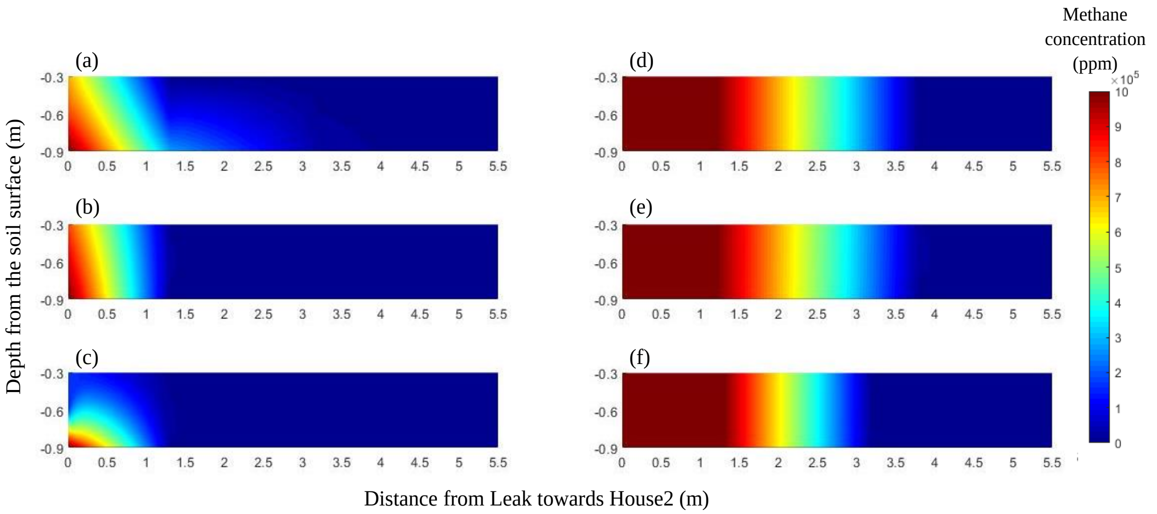

Figure 6: Subsurface expansion of NG plume 6 hrs after starting the releases of (a) 10 slpm in an undisturbed soil with grass cover, (b) 50 slpm in an undisturbed soil with grass cover, (c) 10 slpm release in a frozen soil, (d) 10 slpm release in a dry soil under an asphalt layer, (e) 10 slpm release in a dry soil with an open belowground utility pipe and (f) 35 splm release in a wet soil with grass cover

Conclusions

To better understand fugitive emissions from NG pipelines, we developed a field scale testbed that simulates small to high-pressure gas leaks from belowground natural gas infrastructure. The testbed is fully equipped with subsurface, surface and atmospheric sensors to properly measure and understand the subsurface and atmospheric transient behavior of pipeline leaks and thereby characterize them based on leak properties and controlling parameters. Experimental results demonstrate the testbed's capability to simulate different complexities and properly measure the temporal and spatial variability in NG migrations patterns. In parallel with experiments, numerical simulations are being performed using computational models to guide observations and interpret data. Using the numerical models, the study will vary the conditions more widely than can be done experimentally. Our goal is that the results will provide guidance on leak detection protocols and support development of minimum detection limits (MDLs) under various environmental conditions.

Acknowledgements

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Data Availability Statement

Data sets for this research are available in the in-text data citation reference: *Jayarathne* et al. (2022).

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