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Empirical research on diffusion behavior of leaked gas in the ground

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ABSTRACT

Chemical plants and gas utilities own large underground pipelines to transport material such as combustible gas. For example, city gas utilities in Japan have about 230,000 km of pipelines, even if only the pipelines to deliver gas to their customers are considered. Any accidents involving such pipelines can lead to enormous human and physical damage, and their security is therefore a top-priority issue for utilities. For the safety management of underground pipelines, in addition to assessment of the long-term reliability of pipeline materials, it is extremely important to understand the diffusion behavior of gases in the ground, such as the diffusion range and time, in the case of leakage, and the impact on the surrounding area is a fundamental factor to be considered in the design and maintenance of safe facilities and for emergency response. Although many papers introduce the situations of gas diffusion in the atmosphere such as indoor and outdoor conditions, only fundamental surveys have been conducted on gas diffusion in the ground, and there have been few full-scale empirical studies. This study reports the results of the verification of the diffusion behavior with full-scale gas leakage experiments simulating real underground pipelines, as well as the outcomes of the applicability test of a numerical simulation model investigated and proposed based on the results. This technical knowledge regarding security will contribute to further improvement of safety in the industry.

1. Introduction

1.1. Background and objective

Chemical plants and gas utilities own large underground pipelines to transport material such as combustible gas. For example, city gas utilities in Japan have about 230,000 km of pipelines, even if only the pipelines to deliver gas to their customers are considered. Any accidents involving such pipelines can lead to enormous human and physical damage, and their security is therefore a top-priority issue for utilities. For the safety management of underground pipelines, in addition to the assessment of long-term reliability of pipeline materials, it is extremely important to understand the diffusion behavior of gas in the ground, such as the diffusion range and time, in the case of leakage and demonstrate it on a full-scale level. The impact on the surrounding area is a fundamental factor to be considered in the design and maintenance of safe facilities and for emergency response.

In this study, for empirical investigation and research of security in the supply of combustible gas through underground pipelines, full-scale experiments on underground gas leakage were conducted, and the diffusion behavior including the diffusion range and time was surveyed.

Next, an analytical model considered to be appropriate for simulating the diffusion behavior was surveyed and proposed, and this analytical model was verified by comparing the results of the full-scale experiments with the results of the analysis.

1.2. Survey of existing studies

To clarify the "diffusion behavior of the gas leaked from underground pipelines," it is essential that the three items mentioned below have been studied. In other words, the phenomenon of gas released from the point of leakage into the ground, and diffusing through the pores of soil particles three-dimensionally under various soil conditions is to be clarified. The following items need to be examined for this purpose.

a) It is necessary to examine the behavior caused by differences in pressure, specific gravity and concentration, which are considered to be the main factors in underground gas diffusion when gas of 100 vol% is released from a point of leakage in a pipeline transporting the gas under pressure. It is especially important to consider specific gravity, and the behavior of a gas

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lighter than air and that of a gas heavier than air have to be examined comparatively because combustible gas such as city gas can be of either type.

b) It is necessary that the impact of factors including gas and soil composition and geometric boundary conditions of the ground has been examined.

c) In addition to the behavior in a wide area, the behavior in local zones such as the zone around the point of leakage must have been examined.

It is essential that these issues have been studied from a three-dimensional perspective by, for example, a numerical analytical method based on full-scale empirical experiments and their results. Specifically, it is necessary that the impact on the surrounding area including the diffusion range and time in the ground has been clarified.

From this viewpoint, it was decided to begin this study with the survey of existing studies on the verification of diffusion behavior in the ground with “full-scale experiments on leakage and diffusion” and on the “applicability test of analytical methods” based on such experiments. While many studies of gas diffusion in the atmosphere such as indoor and outdoor conditions have been published in general, there have been only a small number of studies or surveys on the diffusion behavior of leaked gas in the ground. To use the results of existing studies for this research, a wide range of academic data in Japan and other countries about “studies on the behavior of fluid in the ground” were surveyed, and the characteristics of the studies were summarized as follows:

1) Groundwater flow driven by differences in pressure under saturated and unsaturated conditions has been studied (Ewing, Wang, & Weekes, 1999; Faust, 1985; Hibi, 2007; Hwang, Ooka, Sekine, & Ikeuti, 2004; Saito & Kawatani, 2003). While these studies examine the behavior of gas-liquid two-phase flow and liquid phase flow in consideration of environmental pollution, rainwater infiltration and seepage, etc., they research the behavior of gas-liquid two-phase flow and liquid phase flow under saturated and unsaturated conditions and not the behavior of flow that consists mainly of gas.
2) Water-vapor behavior based on temperature and soil water content has been studied (Gerson, Santos, & Mendes, 2003). While this study particularly analyzes the behavior of the water-vapor two-phase system with specific heat, heat conductivity and a diffusion coefficient as the parameters of temperature and soil water content, the subject is the behavior of water and vapor in relation to the temperature and not the behavior of gas diffusion caused by differences in pressure, specific gravity and concentration.
3) Studies of the formation and circulation of gases such as CO_2 and N_2 in the atmosphere-soil-vegetation system in nature have been conducted (Nagai et al., 2004, pp. 1–92; Kumagai, 1998). The subject of these studies is the behavior of one-dimensional vertical formation and circulation of gas on the terrestrial surface and not the three-dimensional diffusion behavior from the point of leakage within a range as wide as a road.
4) Gas diffusion based on particle motion has been studied (Weerts, Kandhai, Bouten, & Sloot, 2001). While the study considers fluid as an aggregate of a large number of particles that repeat collisions and translations and examines the behavior as the regular particle motion of such an aggregate (Lattice-Boltzmann method), the subject is the behavior of gas driven by particle motion in a small area and not the behavior of gas diffusing from the point of leakage due to differences in pressure, specific gravity and concentration in a large area.
5) The diffusion of gas based on difference in concentration has been studied (Arah & Ball, 1994; Egusa, Jinno, & Sumi, 1994; Jin & Jury, 1994; Osozawa & Kubota, 1987). These studies comprise research on the behavior of gas focusing mainly on molecular diffusion caused by differences in concentration and not comprehensive research on the behavior in consideration of differences in pressure, specific gravity and concentration.
6) Gas movement based on differences in concentration, pressure and specific gravity has been studied (Abriola & Pinder, 1985; Akatsuka & Matsuda, 1988; Cheng & Wang, 1996; Falta, Pruess, Javandel, & Witherspoon, 1992; Fujinawa, Hibi, & Fujiwaka, 2001; Iwata, Hamaide, & Fuchimoto, 1992; Joint research of Osaka Gas, Tokyo Gas and Gaz de France, 1989–1992; Kobayashi, Hinkelmann, Helmig, Takara, & Tamai, 2007; Senger et al., 2007; Sleep & Sykes, 1993; Slough, Sudicky, & Forsyth, 1999; Wakoh & Hirano, 1991; Wilson, Montgomery, & Sheller, 1987). While these studies survey the behavior governed by advection and diffusion based on Darcy’s law, they focus on theoretical examination but, in practice, hardly involve any full-scale empirical experimentation or analysis that considers differences in pressure, specific gravity and concentration in a comprehensive manner or examine ground conditions and the situation at the point of leakage.

As indicated above, the movement of water and dissolved materials in the ground is examined in the fields of agriculture and civil engineering as well. Additionally, gas has also attracted attention in the field of environmental geotechnical engineering in recent years, and research subjects include soil pollution and the behavior of hydrogen generated as a result of the corrosion of a nuclear waste container in the clay layer. On the other hand, there are few cases where full-scale experiments have been performed to demonstrate behavior such as the concentration distribution in the ground of the gas of 100 vol% diffusing due to differences in pressure, specific gravity and concentration from 1 to 2 m below the ground under pressure on the assumption of the leakage of combustible gas such as city gas from underground pipelines. Also, there are few cases where the applicability of an analytical model is examined from a three-dimensional perspective based on the results of such full-scale experiments. This study was performed from such a perspective.

2. Survey of diffusion behavior with full-scale experiments on gas leakage in the ground

2.1. Outline of the experiments

A full-scale experiment site that modeled an ordinary chemical plant site along with part of a road was constructed. As the leaked gas, two types of typical combustible gases with different specific gravities were used: CH_4, which has a lower specific gravity than air, and propane air 13A (propane 60 vol% and air 40 vol%, hereinafter “PA13A”), which has a higher specific gravity than air. Leakage from corroded pores and pipe joints of the above-mentioned long-distance underground pipelines that deliver gas to the customers was assumed. Leakage from large pores generated as a result of damage by heavy equipment such as civil engineering machinery and leakage from high-pressure pipelines were not considered because such types of leakage can be immediately discovered by detecting the gas emitted into the atmosphere and the pipelines can be repaired to stop the leakage. Accordingly, this study covered only the leakage that causes concern about the movement of gas for security reasons such as the above-mentioned types of leakage. The amount of leakage was assumed to be around 300–1000 cc/min (the pressure was set to be 0.2 kPa, which was