Contaminant leakage detection system using a grid-net electrical conductivity measurement method

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Abstract

The concept that the electrical properties of a subsurface can be affected by the leakage of contaminants might be applicable for a leakage detection system for petroleum hydrocarbons and landfill leachate. Detection systems using electrical conductivity measurement are advantageous since they are fast and efficient methods which require little data processing in order to obtain accurate and repeatable results. A grid-net electrical conductivity measuring method had been developed as a means of two-dimensional monitoring of leaking contaminants in a target area. In this study, the optimum electrode spacings of a two-electrode sensor were found for leachate and diesel fuel. Then laboratory model tests were performed to evaluate the direct application of a grid-net electrical conductivity measurement system for the detection of landfill leachate and diesel fuel. In the laboratory model test results, landfill leachate and diesel fuel leakage were accurately identified by the grid-net electrical conductivity measurement system. Keywords: leakage detection system, electrical conductivity, landfill leachate, diesel fuel.

1 Introduction

In geoenvironmental engineering, detecting and monitoring subsurface contamination is essential process in preventing environmental disasters. Landfill leachate leakage in solid waste landfills and petroleum hydrocarbons leakage in the underground storage tanks have been a chief cause of groundwater and subsurface contamination. Laine and Darilek [1] reported that an average of
22.5 leaks per 10,000 m$^2$ of geomembrane liner have been found. And USEPA [2] stated that approximately 25% of all USTs in USA experience leakage.

Standard methods of leakage detection primarily rely upon numerous soil and groundwater sampling for laboratory analysis. The site must be extensively drilled for sampling in order to delineate the location and the amount of contamination present [3, 4]. Thus, sampling is a laborious and destructive method which is inappropriate for continuous monitoring of subsurface contamination. In order to overcome such limitations, it is necessary to develop a non-destructive and efficient method which is able to monitor subsurface continuously with time to minimize environmental damage by detecting leakage at an early stage. Continuous in situ monitoring in the subsurface using electrical methods has been proposed as an alternative to direct sampling [4, 5, 6, 7]. The electrical method for leakage detection is based on the concept that electrical properties of subsurface materials undergo changes by contaminant intrusion. Such changes in electrical properties can be represented by using the electrical conductivity measurement. Contaminants alter the electrical properties and thus the electrical conductivity of the soil and groundwater, which indicate possibilities of subsurface monitoring by interpreting deviations in electrical conductivity. Detection system using electrical conductivity measurement is advantageous since it is a fast and efficient method which requires little data processing in order to obtain accurate and repeatable results [8].

In this study, grid-net electrical conductivity measuring method was developed as a means of two-dimensional monitoring of target area. This method is based on direct measurement of contaminant intrusion thus enables detection regardless of the type of containment system. Laboratory model tests were performed to evaluate its potential application for monitoring leakage of both landfill leachate and diesel fuel as contaminant source.

2 Grid-net electrical conductivity measurement system

The grid-net electrical conductivity measurement system consists of three parts; 1) grid-net electric circuit, 2) electrical conductivity measuring sensors adapting two electrodes measurement method, and 3) measurement instruments including connection system, source meter and data logger as shown in fig. 1 [9].

The grid-net electric circuit is based on installing two perpendicular sets of horizontal electric wires in specific intervals with sensors located at their intersections. The sensors are directly installed in the subsurface to measure electrical conductivity. Measurement is performed by connecting the (+), (-) terminal of the source meter to two grid wires that lead to one of the two electrodes of a specific sensor, which completes a closed circuit. For example, in fig. 1, the electrical conductivity measurement of sensor located at (i, j) is accomplished by connecting both wires i and j to the source meter. The electrical conductivity at a sensor of a closed circuit is obtained by measuring electrical potential under the application of a constant current using a source meter. Measurements at all sensors are achieved by connecting the wires to the source.
meter in series. The location of contaminant intrusion is found by searching for deviation points in the distribution of electrical conductivity or resistivity.

Figure 1: Schematic diagram of grid-net electrical conductivity measurement system.

3 Experimental section

3.1 Test materials

Soil tested for this study is weathered granite soil, which is abundant in Korea. Weathered granite soil is classified as well-graded sand (SW) under the Unified Soil Classification System (USCS). The index properties of soil used in this study are summarized in table 1. Landfill leachate and diesel fuel are used as the contaminants. Landfill leachate used in this study was collected from Gimpo municipal landfill, Korea. Tap water was used as the pore water for the uncontaminated soils. The conductivity of tap water was measured at 25°C by conductivity meter (ORION 550A), which was measured as 0.15 mS/cm.

Table 1: Index properties of soil.

<table>
<thead>
<tr>
<th>gravel fraction</th>
<th>sand fraction</th>
<th>silt/clay fraction</th>
<th>gradation coefficient</th>
<th>uniformity coefficient</th>
<th>specific gravity</th>
<th>organic content</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1%</td>
<td>93.2%</td>
<td>4.7%</td>
<td>1.4</td>
<td>8.4</td>
<td>2.63</td>
<td>1.97%</td>
</tr>
</tbody>
</table>

3.2 Preliminary tests

In order to determine the optimum electrode spacing between two electrodes that compose a sensor in the grid-net electrical conductivity measurement
system, preliminary tests were performed as shown in fig.2. Contaminant was introduced in between the two electrodes which were installed with four different spacings of 1.5cm, 3.5cm, 5.5cm and 7.5cm. The objective of this preliminary test was to determine the degree of sensor ability to detect contaminant intrusion according to varying electrode spacing. Electrical conductivity measurement was performed on sample soil placed in an insulated plastic container with dimensions 20cm×14cm×12.5cm(height), which was considered to be big enough to withhold any hindrance in the flow of electric current.

The sample soil was weathered granite soil which was prepared by mixing tap water uniformly to have a controlled water content. It was then compacted by dropping a 2.5kg hammer 25 times from a height of 20cm. The two-electrode sensors with different electrode spacing were installed on sample soils prepared in this identical procedure to measure the electric current and potential in the Keithley 2400 instrument. The electrical conductivity was calculated with the measured electric current and potential values under the Ohm's law. In order to determine the degree of sensor ability to detect contaminant intrusion, contaminant was introduced in a manner to depict field situation as shown in fig. 2(b). Electrical conductivity of the prepared soil sample was measured before and after releasing 50mL of contaminant solution in the center of the two electrodes by using a pipette. In this study, diesel fuel and landfill leachate used to compare the measured electrical conductivity values before and after contaminant injection. In addition, the degree of sensor sensitivity for the two different contaminant solutions was determined.

![Diagram](image.png)

Figure 2: Four types of two-electrode sensors and schematic diagram of preliminary test method.

3.3 Laboratory model tests

Laboratory model tests were performed to evaluate the direct application of detecting contaminant leakage with the use of the grid-net electrical conductivity measurement system. A soil box with dimensions of 120cm×120cm×50cm(height) was prepared for laboratory model test. After soil
box is filled with weathered granite soil and compacted, two perpendicular sets of five horizontal electric wires at 20cm intervals were installed in soil to form a grid-net. Then 25 electrical conductivity measuring sensors were installed in the soil at each wire. After the installation of the grid-net electric circuit with sensors, connecting the branch wires of the grid-net circuit to a measuring instrument system completed the model set up. Fig. 3 shows the soil box and model test set-up. The digital source meter (Keithley 2400) was used to induce the constant current of 0.1mA and measure the electrical potential.

Oh et al [10] have shown that the electric circuit effects were developed in grid-net measurement system and can be effectively excluded by a process of calibration using P-SPICE (Professional Simulation Program with Integrated Circuit Emphasis) simulation. Therefore, in this study, to obtain the actual electrical conductivity distribution excluding the electric circuit effect, P-SPICE simulation were performed and laboratory experimental data were calibrated.

(a) Schematic diagram of model test  (b) grid-net electric circuit in model test

Figure 3: Schematic diagram of soil box and grid-net electric circuit in laboratory model test.

4 Results and analysis

4.1 Preliminary test results

Electrical conductivity of soil increased with water content as shown in fig. 4. This is a desirable result since water is the dominant factor that controls the electrical conductivity of soil, except for high specific surface minerals in high resistivity fluid [9].

In order to evaluate the change in electrical conductivity according to the type of contaminant and determine the optimum electrode spacing for contaminant detection, comparisons were made on the measurements of electrical conductivity that took place before and after contaminant intrusion. Fig. 5 shows the change in electrical conductivity of soil affected by landfill leachate and diesel fuel intrusion. Intrusion of diesel fuel which is a non-conducting contaminant decreased the electrical conductivity due to its hindrance on electrical current path formation. On the contrary, intrusion of landfill leachate increased the electrical conductivity by providing increase in water content and ion concentration.
The electrical conductivity is independent of a sensor’s electrode geometry. As illustrated in Fig.4, measurement of electrical conductivity using the two-electrode method on soils that are homogeneously mixed with water gives an identical value for various electrode spacing. However, when contaminant is released into the subsurface, it creates a non-homogeneous distribution of contaminant concentration in the subsurface during its initial stage of intrusion. In this case, the electrical conductivity is affected by the electrode spacing. In order to increase the effectiveness of the sensors in providing electrical conductivity measurements to be used for contaminant detection, measurements that take place before and after the contaminant intrusion must give values that have a significant numerical difference. On this basis, Fig. 5 shows that a considerably large electrode spacing of 7.5cm for landfill leachate which is a
conductive contaminant, and a comparably small spacing of 1.5cm for diesel fuel which is a non-conductive contaminant, are the optimum selections of electrode spacing. Such results can be interpreted in terms of the electrical current paths that take place over a greater area when electrode spacing is increased. Namely, although non-conductive contaminants such as diesel fuel do not mix with pore water and result in hindering formation of current paths, the decrease in electrical conductivity is reduced at large electrode spacing due to possible conduction over electrical current that take place through round-about paths. Therefore, the effectiveness of sensor is affected by the electrode spacing according to the electrical properties of target contaminant. As a result, if sensors are to be used for contaminant detection, considerations should be made on the electrode spacing in order to increase their effectiveness to contaminant intrusion.

![Diagram](image)

(a) initial condition

(b) after 1L leakage

Figure 6: The distribution of electrical conductivity in model test in the case of leaking landfill leachate.
4.2 Model test results

Laboratory model tests were performed on the bases of the preliminary test results. The electrode spacing of two-electrode sensor in the model test is set up to 7.5cm in the case of leachate and 1.5cm in the case of diesel fuel. In model tests, the initial electrical conductivity at each sensor was measured before contaminant was introduced. Then the electrical conductivity at each sensor was measured after continuous release of 1L leachate and diesel fuel into the subsurface at a selected point.

![Initial Condition](image1)

(a) initial condition

![After 1L Leakage](image2)

(b) after 1L leakage

Figure 7: The distribution of electrical conductivity in model test in the case of leaking diesel fuel.
4.2.1 Landfill leachate
Fig. 6(a) shows the initial distribution of electrical conductivity in the subsurface without any landfill leachate leakage. In fig. 6(a), electrical conductivity values of the subsurface before leachate injection lie within the small range of 13.3-20.7 µS/cm. Fig. 6(b) shows the distribution of electrical conductivity in the tested site after leachate leakage occurred. Spikes in the distributions of electrical conductivity as shown in fig. 6(b) correspond to the locations of landfill leachate leakage. The area without any intrusion of leachate showed constant electrical conductivity. The area with leachate intrusion showed three times higher electrical conductivity, which indicated that the leachate intrusion increased the electrical conductivity in the released area. Actually, the electrical conductivity at leaking point increased by 87.1 µS/cm, while electrical conductivities of other locations without any intrusion of leachate remain within the ranges of 14.8-25.4 µS/cm. This result indicates that leakage of landfill leachate is accurately identified by the grid-net electrical conductivity measurement system.

4.2.2 Diesel fuel
Fig. 7(a) shows the initial distribution of electrical conductivity in the subsurface without any diesel fuel leakage. In fig. 7(a), electrical conductivity values of the subsurface before diesel fuel injection lie within the small range of 21.1-26.4 µS/cm. Fig. 7(b) shows the distribution of electrical conductivity in the tested site after diesel fuel leakage occurred. The electrical conductivity at leaking point decreased by 4.4 µS/cm, while electrical conductivities of other locations without any intrusion of diesel fuel remain within the ranges of 19.2-27.3 µS/cm. This result indicates that leakage of diesel fuel is accurately identified by the grid-net electrical conductivity measurement system.

5 Conclusions
The following conclusions are drawn from laboratory preliminary tests and model tests.

Preliminary tests were preformed to determine the optimum electrode spacing for different contaminant types. The results of laboratory model tests indicate that the grid-net electrical conductivity measurement system can be applicable to the detection of landfill leachate and diesel fuel, and thus has great potential for monitoring of contaminant leakage.

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References


