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Application of optimized time domain reflectometry probe for estimating contaminants in saline soil

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Abstract. Monitoring contaminants in waste landfills on a seabed is important because the leachate affects the marine ecosystem and facility stability. The objective of this study is to optimize a time-domain reflectometry (TDR) probe using different coating materials and several electrodes to estimate contaminants in saline soil. Copper concentrations ranging from 0 mg/L to 10 mg/L were mixed in 3% salinity water to simulate contaminants in the ocean environment. Epoxy, top-coat, and varnish were used as coating materials, and two to seven electrodes were prepared to vary the number and arrangement of the electrodes. Test results showed that the varnish stably captured the increase in copper concentration, while the other coating materials became insensitive or caused leakage current. In addition, a TDR probe with more electrodes exhibited stable and distinct electromagnetic signals. Thus, the TDR probe with seven electrodes coated with varnish was effectively used to estimate contaminants in saline soil.

Keywords: coating materials; copper concentration; electrodes; final converged voltage; time domain reflectometry

1. Introduction

As urban development accelerates in several countries surrounded by the sea (for example, South Korea, Japan, Singapore), waste landfilling on seabeds is being broadly conducted owing to the lack of limited territory (Hong *et al.* 2022). Japan particularly has constructed more than 40 waste landfill facilities on the seabed, while Singapore has built the Semakau Island, which is artificially made from waste dumping (Park *et al.* 2016). For waste landfills on seabeds, the leakage of contaminants directly affects the marine ecosystem and reduces the stability of the landfill (Kahlouche *et al.* 2021, Raheem and Omar 2021). Previous studies investigated the shielding efficiency of waste landfill barriers designed to filter contaminants in underground water (Bonaparte and Gross 1990, Clément *et al.* 2010). In addition, leaked water was monitored using detecting sensors, such as electrodes, to indirectly estimate barrier integrity (Lee *et al.* 2019, Li *et al.* 2022, Oh *et al.* 2001).

Electrical resistivity surveys have generally been used to monitor groundwater contaminants in hydrogeological fields (Benson *et al.* 1997, Cherry *et al.* 1983). Electrical resistivity, contrarily to electrical conductivity, is simple and direct to estimate contaminants since landfill leachate has an apparently low electrical resistivity (Buselli and Lu 2001). Electrical resistivity imaging (ERI) was efficiently used for groundwater monitoring among traditional hydrogeological methods because observation wells were not required (Park *et al.* 2016). For waste landfills on seabeds, however, the electrical resistivity survey was limited because that of seawater was low although it was not contaminated (Mas-Pla *et al.* 2013). Consequently, the effect of slight contaminants in seawater was difficult to identify. In addition, the electrical resistivity survey was fundamentally uncertain owing to the fluctuations in electrical signals caused by contact problems (Calamita *et al.* 2017).

Time-domain reflectometry (TDR), which receives electromagnetic signals, was employed to capture contaminants, including heavy metal solutes (Mojid *et al.* 2016). Hong *et al.* (2022) used the TDR probe to estimate the bulk electrical conductivity in a saline medium and coupled it with machine learning. Although TDR can be used when the electrical conductivity changes considerably (Vogeler 2001), the penetration-type TDR probe can improve the contact problems of electrical resistivity surveys. However, the TDR probe, which comprises several electrodes, can corrode when exposed to seawater containing heavy metal contaminants (Atta *et al.* 2015, Yeh *et al.* 2006). In addition, uncertainty or sensitivity vary depending on the number of electrodes in the TDR probe (Suwansawat and Benson 1999, White and Zegelin 2018).

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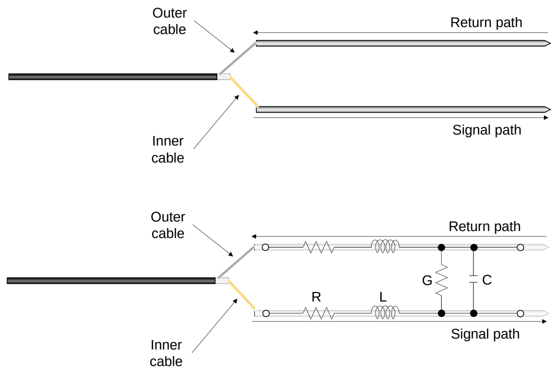


Fig. 1 Equivalent circuit model of signal and return paths in TDR probe

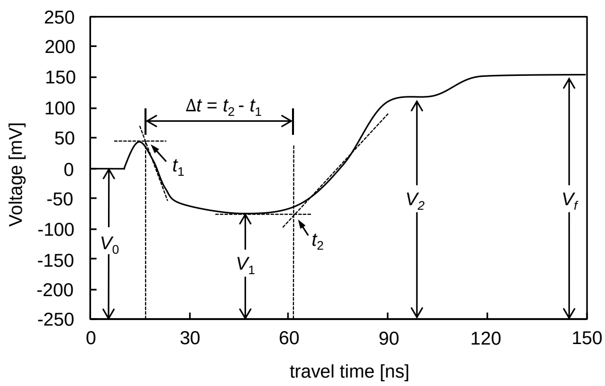


Fig. 2 Typical electromagnetic signal measured by time domain reflectometry

The objective of this study is to optimize and verify the TDR probe using different coating materials and several electrodes to estimate the quantity of contaminants in seawater. This paper begins with a brief description of time domain reflectometry principles and introduces the designed TDR probe and measurement system. Then, the experimental results of the TDR probes using different coating materials and several electrodes are presented. Finally, the sensitivities of the electromagnetic signals are analyzed and the electrical characteristics discussed.

2. Experimental setup

2.1 Principle of time domain reflectometry

TDR is a method for measuring electromagnetic signals reflected at the impedance change point in transmission lines (Chung and Lin 2011). The electromagnetic signal acquired from the TDR probe varies with permittivity and electrical conductivity because it is influenced by the electrical characteristics of the coating material of the probe. For this reason, a transmission line composed of signal and return paths conveyed the propagation and reflection of signals, respectively. A coaxial cable containing inner and outer lines is typically used as transmission line, as shown in Fig. 1. Fig. 1 shows that the inner and outer lines were connected to the signal and return paths, respectively. The transmission line was expressed as an equivalent circuit model comprising resistance (R), inductance (L), conductance (G), and capacitance (C), as presented. R and L represent an electrical quantity opposing the current flow and magnetic energy stored in the transmission line, respectively. Meanwhile, G and C account for the electrical energy loss owing to leakage current into dielectric materials and the capacity to store charges between conductors, respectively (Yu *et al.* 2020).

The velocity of electromagnetic waves flowing through the TDR probe mainly depends on the inductance and capacitance of the material. The velocity of electromagnetic waves (V_P) can be expressed as follows

$$V_P = \frac{1}{\sqrt{LC}} = \frac{1}{\sqrt{\varepsilon_0 \varepsilon_r \mu_0 \mu_r}} = \frac{c_0}{\sqrt{\varepsilon_r \mu_r}} \quad (1)$$

where ε_0 and μ_0 denote the permittivity and magnetic permeability in a vacuum, respectively. ε_r and μ_r are the relative permittivity (dielectric constant) and relative magnetic permeability, respectively, and c_0 is the reference value of the electromagnetic wave velocity in vacuum (3.0 × 10^8 m/s). In addition, μ_r generally has a value of 1.0, owing to the non-magnetic characteristics of soil materials.

Then, V_P was simplified as follows

$$V_P = \frac{c_0}{\sqrt{\varepsilon_r}} = \frac{2l}{\Delta t} \quad (2)$$

where l and Δt are the lengths of the TDR probe and travel time, respectively. Finally, the relative permittivity was determined from the electromagnetic signal as

$$\varepsilon_r = \left(\frac{c_0 \Delta t}{2l}\right)^2 \quad (3)$$

Thus, the electromagnetic signal varied depending on the relative permittivity of the materials between the signal and the return paths. In other words, a change in the relative permittivity of the materials will determine the electromagnetic signal pattern, which makes the voltage values to fluctuate.

Further, the electrical conductivity of the materials can be obtained from the electromagnetic signal (Hong *et al.* 2019, Kim *et al.* 2021. The waveform of electromagnetic signals is known to be related to the electrical conductivity of the materials (Jones *et al.* 2002, Kim *et al.* 2018, Lee *et al.* 2020). An electromagnetic signal measured by time-domain reflectometry is illustrated in Fig. 2. Δt is defined as the travel time of the propagation of the electromagnetic wave through the TDR probe, and t_1 and t_2 are the times at which the electromagnetic wave reaches the front and the end of the TDR probe, respectively. The characteristic voltages are presented as V_x, where V_0 is the input voltage of the time-domain reflectometer, and V_1 and V_2 are the voltages of reflected signals at the end of the TDR probe, respectively. V_f is the final voltage of the electromagnetic signal, where sufficient time elapsed. Previous studies have proposed several equations for the estimation of electrical conductivity using the characteristic voltages from the electromagnetic signal, as summarized in Table 1 (Muñoz-

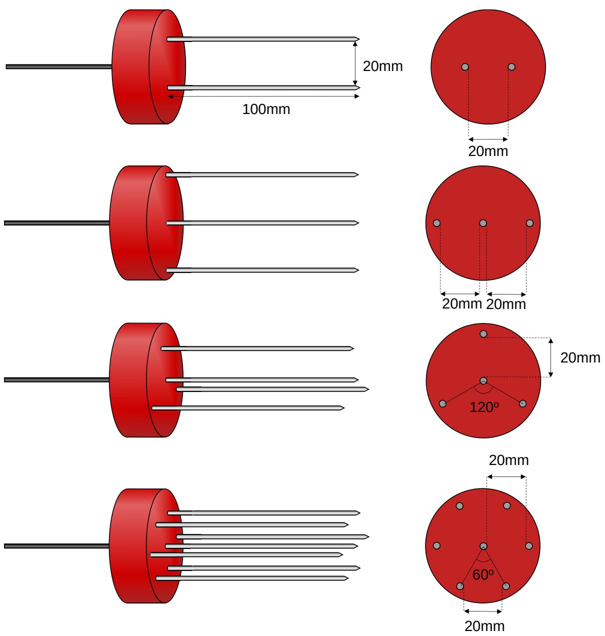


Fig. 3 Schematic drawing of TDR probes with different number of electrodes

Carpena *et al.* 2005, Dalton and Van Genuchten 1986, Giese and Tiemann 1975, Topp *et al.* 1988). According to Eq. (3), relative permittivity is a function of the travel time and length of the TDR probe. Thus, electrical conductivity can be calculated from the waveform of electromagnetic signals and length of the TDR probe using suggested equations.

2.2 Time domain reflectometry probe

Time domain reflectometry probes using different numbers of electrodes and arrangements were designed to estimate the quantity of contaminants in the saline soil, as shown in Fig. 3. Fig. 3 shows that the TDR probes were composed of two, three, four, and seven electrodes. Time domain reflectometry probes are generally composed of one central conductor and one to six outer electrodes, which determine the electromagnetic field and act as a ground (Campbell, 1990, Heimovaara 1994). Hence, the central electrode was equivalently connected to the inner coaxial cable to be used as a signal path and the other electrodes were soldered to the outer coaxial cable as return paths. All electrodes were designed to be 100 mm in length and 2 mm in diameter, while the distance between the electrodes was maintained at 20 mm. The distance between the electrodes in the TDR probe were 10 times greater than the diameter of the electrodes (Knight 1992, Noborio 2001). The tips of the electrodes were sharpened for further penetration into the ocean sediments. In addition, the electrodes were coated with different materials for insulation since the high conductivity of the saline water can cause leakage current (Fujiyasu *et al.* 2004). Epoxy, top-coat, and varnish were adopted as coating materials because they have been widely used for providing insulation in marine environments (Wang *et al.* 2016, Zhang *et al.* 2016). Epoxy coating was divided into single and double-coated cases. The thickness of single-coated epoxy, top-coat, and varnish were 0.15 mm, while that of double-coated epoxy was 0.25 mm.

2.3 Measurement system

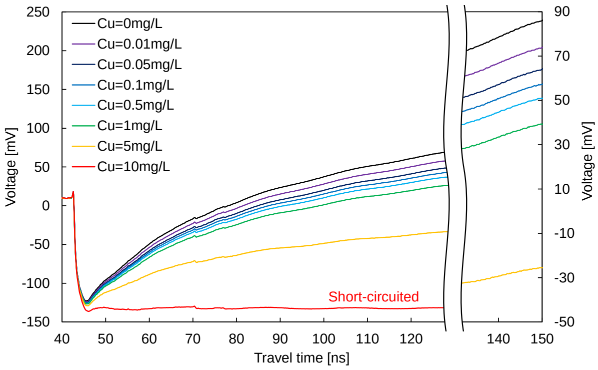
Copper was used as a contaminant because it is easily detected in waste incineration regions (Lee *et al.* 2018). Copper concentrations of 0, 0.01, 0.05, 0.1, 0.5, 1, 5, and 10 mg/L were used to vary the gradation of the contaminants. Three percent salinity water was used to simulate the ocean environment and the temperature was maintained at 19°C.

The TDR probe was in direct contact with water at different copper concentrations to evaluate the influence of the coating materials and number of electrodes. Thereafter, the optimized TDR probe was selected and injected into soils that simulated ocean sediments. All the TDR probes were soldered to a coaxial cable (RG58C/U) with a characteristic impedance of 50 Ω, and the coaxial cable was connected to a time-domain reflectometer (HL1101, Hyperlabs) whose input voltage is 250 mV. A total of 256 data points were stacked and collected for each electromagnetic signal. They were then visualized and stored using a computer.

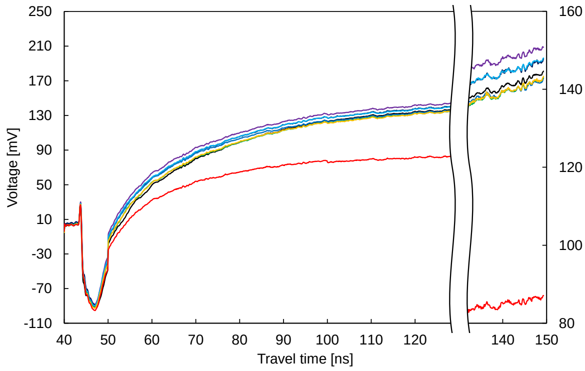
3. Experimental results

3.1 Coating materials

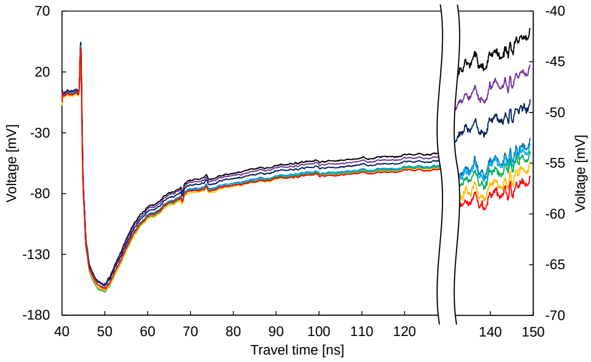
The measured electromagnetic signals with different coating materials (single-coated epoxy, double-coated epoxy, top-coat, and varnish) for the TDR probe with three electrodes are presented in Fig. 4. Fig. 4 shows that the voltages for all cases decreased as the copper concentration increased. However, for the single-coated epoxy in Fig. 4(a), the voltage gradually decreased as the copper concentration increased from 0 mg/L to 1 mg/L and significantly decreased at a copper concentration of 5 mg/L. Thereafter, the electromagnetic signal was completely attenuated (that is, short-circuited) when the copper concentration reached 10 mg/L. Note that the electromagnetic signal is unchanged above the copper concentration of 10 mg/L; hence, the short-circuited signal was determined at 10 mg/L. As a result, the single-coated epoxy was limited in preventing leakage current when the copper concentration was high. Moreover, the voltage of double-coated epoxy in Fig. 4(b) varied slightly from the copper concentration, from 0 mg/L to 0.5 mg/L, and decreased from 0.5 mg/L to 5 mg/L. Then, the voltage decreased considerably at a Cu concentration of 10 mg/L. Consequently, the double-coated epoxy prevented leakage current at high copper concentrations compared to the single-coated epoxy. However, the copper concentration in the extremely low range could not be discriminated upon owing to the large thickness of the coating. For the top-coat in Fig. 4(c), the voltage decreased as the copper concentration increased from 0 mg/L to 0.1 mg/L and slightly decreased when the copper concentration increased above 0.1 mg/L. Thus, the top-coat became insensitive at a relatively high copper concentration. Meanwhile, the voltage of the varnish in Fig. 4(d) gradually and



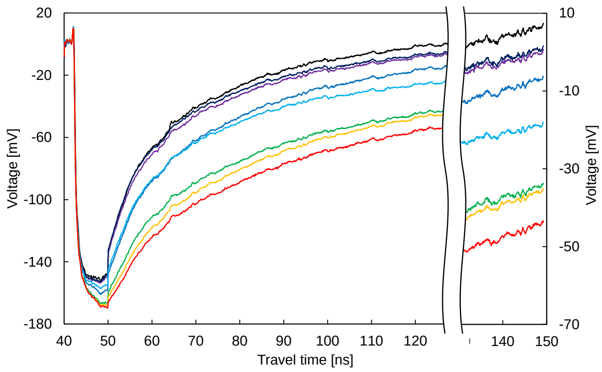
(a) Single-coated epoxy



(b) Double-coated epoxy



(c) Top-coat



(d) Varnish

Fig. 4 Typical electromagnetic signals with different coating materials

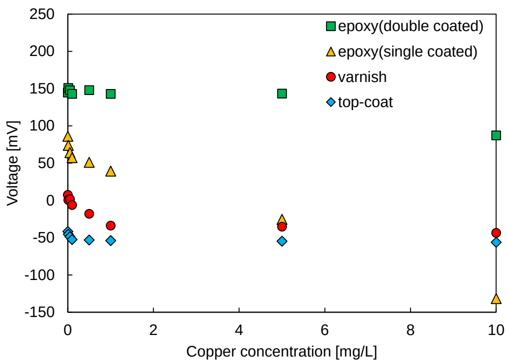


Fig. 5 Voltages at the travel time of 150 ns from different coating materials with respect to copper concentration

continuously decreased with an increase in copper concentration from 0 to 10 mg/L.

For the overall evaluation and comparison of the coating materials, the values of the voltage at a travel time of 150 ns are plotted in Fig. 5. Fig. 5 shows that all the coating materials except the double-coated epoxy could determine the variation of low copper concentration from 0 mg/L to 0.1 mg/L. For a medium copper concentration of 0.1 mg/L 1 mg/L, the top-coat was unsuitable because the difference between voltages was insignificant. In addition, single-coated epoxy could not be applied at high copper concentrations of 1 mg/L to 10 mg/L owing to the short-circuit problem, though it was the most sensitive material in that range of copper concentrations.

3.2 Electrodes

The electromagnetic signals received by the TDR probe with two, three, four, and seven electrodes are shown in Fig. 6. Note that the varnish was identically selected as a coating material for all electrodes cases. Fig. 6 shows that the voltages for all cases decreased with an increase in the copper concentration, which is similar to the voltage variation in Fig. 4. In addition, the voltage slightly decreased as the copper concentration increased from 0 mg/L to 1 mg/L and considerably decreased above the copper concentration of 1 mg/L. For the TDR probe with two electrodes, the measured electromagnetic signals in Fig. 6(a) showed unstable waves compared to the TDR probe with additional electrodes. When an additional electrode was added to the return path (that is, a TDR probe with three electrodes), the electromagnetic signals became relatively stable. However, the difference between final converged voltages becomes narrower, as shown in Fig. 6(b). Consequently, the TDR probe with four electrodes distinguished the voltages between different copper concentrations, as shown in Fig. 6(c). Finally, the TDR probe with seven electrodes, which includes the greatest return paths in this study, revealed the most stable electromagnetic signals, as shown in Fig. 6(d).

To compare the number of electrodes, the voltages at a travel time of 150 ns were plotted as shown in Fig. 7. Fig. 7 shows that the voltage decreased with a higher number of electrodes, which was similarly observed by Suwansawat and Benson (1999). In addition, the voltage rapidly

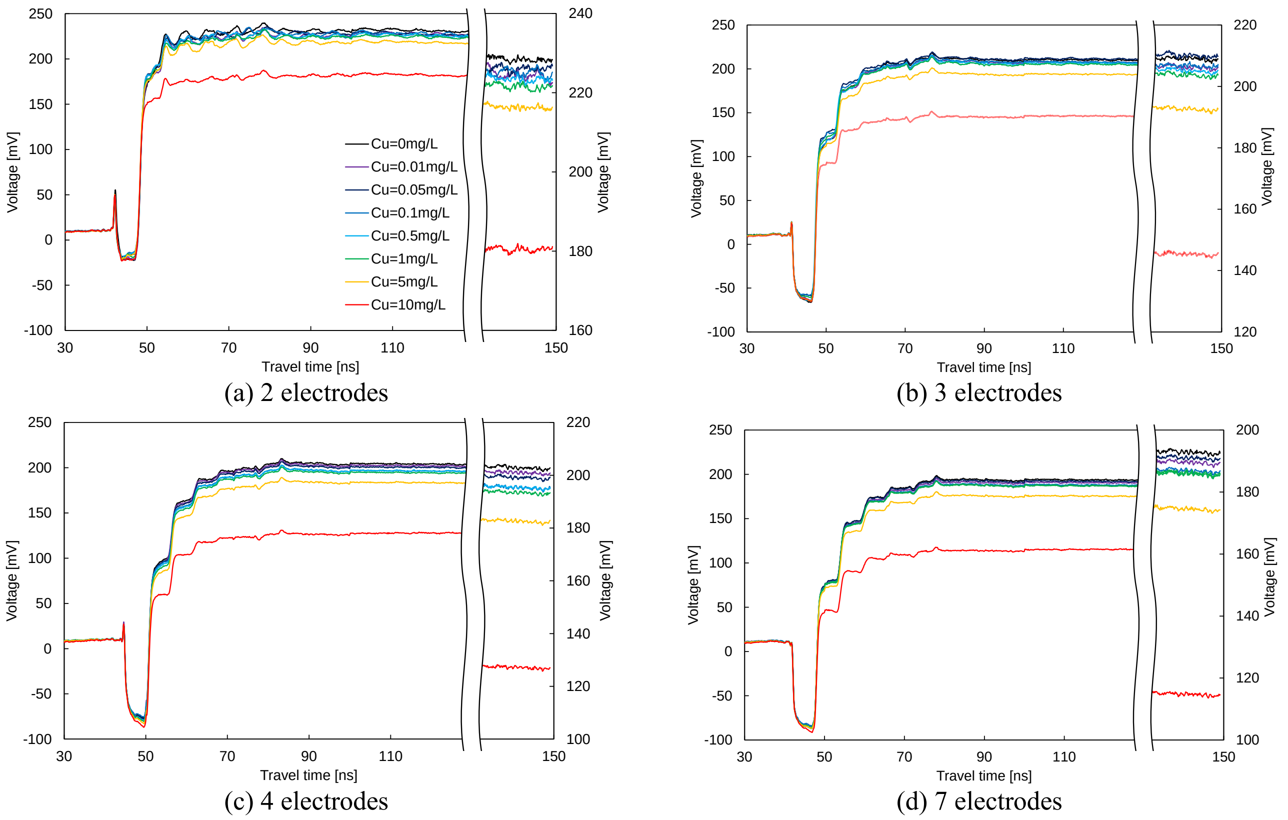


Fig. 6 Typical electromagnetic signals with different number of electrodes

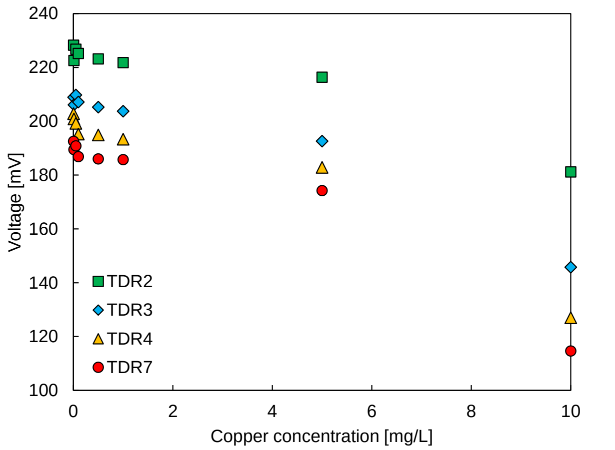


Fig. 7 Voltages at the travel time of 150 ns from different number of electrodes with respect to copper concentration

decreased at low copper concentrations from 0 mg/L to 0.1 mg/L, gradually decreased at medium copper concentrations from 0.1 mg/L to 1 mg/L, and significantly decreased at high copper concentrations from 1 mg/L to 10 mg/L. The TDR probe with two electrodes was unsuitable for detecting low copper concentrations because the voltages were not displayed in order of copper concentration. Similarly, it was relatively difficult for a TDR probe with three electrodes to determine the difference between voltages at low copper concentrations. Time domain reflectometry (TDR) probes with four and seven electrodes detected and discriminated between different copper concentrations with stable electromagnetic signals (see Figs. 5(c) and 5(d)).

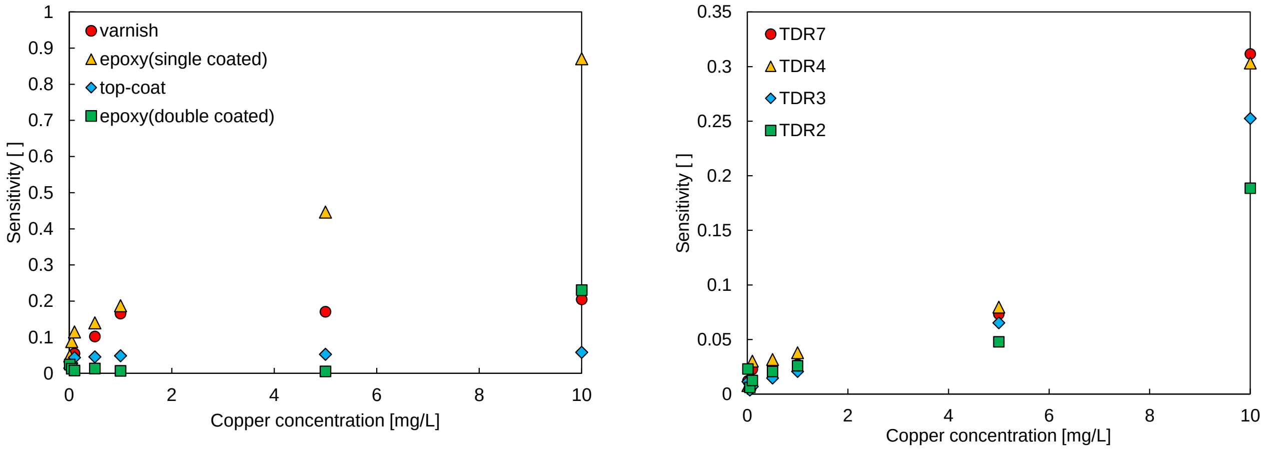
4. Analyses and discussion

4.1 Sensitivity

To compare the susceptibilities of the various coating materials and different numbers of electrodes, the sensitivity was determined as follows

$$Sensitivity = [V_{f\,(\mathrm{Cu=0\,mg/L})} - V_{f\,(\mathrm{Cu}=x\,\mathrm{mg/L})}] / V_{input} \tag{4}$$

where V_{input} is input voltage of measurement system, V_f and Cu are the final voltage and copper concentration, respectively. In this study, V_f is defined as the voltage at the travel time of 150 ns since V_f does not converge for the travel time of more than 2000 ns. The sensitivities of the coating materials and number of electrodes with respect to the copper concentration are plotted in Fig. 8. Fig. 8(a) shows that the sensitivity increases in the sequence of double-coated epoxy, top-coat, varnish, and single-coated epoxy. Epoxy has received credit from marine coatings for its anti-corrosive and self-healing properties that restrict the invasion of aggressive ions (Atta *et al.* 2015, Yeh *et al.* 2006). Thus, the double-coated epoxy successfully protected the TDR probe. However, it resulted in an extremely low sensitivity. In addition, epoxy has been used



(a) Coating materials (b) Number of electrodes

Fig. 8 Sensitivities with respect to copper concentration

for electronic packaging owing to its role as an integral capacitor and its co-integration with integral resistors and inductors (Ahmadi 2019). The conductance is inversely proportional to the resistance; therefore, the conductance increases as the thickness of the coating material decreases (Bhattacharya and Tummala 2001). Thus, a short circuit occurs in the single-coated epoxy when the copper concentration is high (see Fig. 4(a)), and it is unsuitable for the estimation of contaminants in saline soil despite having the highest sensitivity. The top-coat is a typical marine coating system exposed to contaminants, chlorides, oxygen, and humidity, which induce corrosion and aging (Zhang *et al.* 2016).

They demonstrated that the entire coating material retained a high impedance, even though some defects were generated on the coating surface during marine exposure. Similarly, the top-coat presents stable electromagnetic signals from this study (see Fig. 5); however, the sensitivity is severely low as like double-coated epoxy. In the end, the sensitivity of varnish is relatively high compared to that of the top-coat and double-coated epoxy and does not induce short-circuits, as in the single-coated epoxy. For this reason, varnish has been widely used to explore corrosion and degradation behaviors in simulated marine environments or seawater (Wang *et al.* 2016, Xiao *et al.* 2012).

Fig. 8(b) shows that the sensitivity exhibits a higher value with a greater number of electrodes. For the TDR probes with two and three electrodes, the electromagnetic signals became stable and narrow as the number of electrodes increased (see Figs. 5(a) and 5(b)), resulting in a lower and consistent sensitivity for low and medium copper concentrations. White and Zegelin (2018) revealed that a TDR probe with two electrodes produced an unbalanced signal, which led to noise and signal loss. The noise in electromagnetic signals may cause errors in determining the travel distance and apparent dielectric constant (Suwansawat and Benson 1999). Furthermore, the TDR probe with two electrodes has a greater risk of encountering deviated voltages and currents than that with three electrodes (Topp and Davis 1985). A TDR probe with more than three electrodes provides more balanced electromagnetic signals, avoiding the balun requirement (Zegelin *et al.* 1989). In this context, the electromagnetic signals became more stable with respect to the number of electrodes (see Figs. 5(c) and 5(d)). Jones *et al.* (2002) demonstrated that a TDR probe with seven electrodes could sample a large and concentrated soil volume around the center electrode, which may be desirable for routine measurements. In addition, the sensitivity estimated by the TDR probe with seven electrodes was highest when the copper concentration reached 10 mg/L.

4.2 Electrical characteristics

From the evaluation of the influence of the coating material and the number of electrodes, a TDR probe with seven electrodes coated with varnish was adopted as an optimized case. Subsequently, the optimized TDR probe was verified to reliably assess contaminants in the saline soil. Electromagnetic signals were obtained in water with different salinities using a manufactured TDR probe for calibration with electrical conductivity. The electrical conductivities of water with different salinities were measured by conductivity meters. Electromagnetic signals were gathered for water with different salinities, and the electrical conductivities were measured, as shown in Fig. 9. Fig. 9 shows that the voltage at the travel time of 150 ns, which corresponds to V_f, decreases as the measured electrical conductivity increases. The gathered electromagnetic signals were analyzed to estimate V_0, V_1, V_2, and V_f, and the values were substituted into the equations (see Table 1). The estimated electrical conductivities are plotted against the measured electrical conductivity in Fig. 10. Note that the estimated bulk electrical conductivity is extremely lower than the measured conductivity due to the resistance of coating material. Fig. 10 shows that the estimated electrical conductivity from Giese and Tiemann (1975) presents a linear relationship with the measured electrical conductivity, whereas those from Dalton and Van Genuchten (1986) and Topp *et al.* (1988) exhibit an unstable relationship. The equation from

Table 1 Equations of electrical conductivity with characteristic voltages (Muñoz-Carpena *et al*. 2005)

Equations	Reference	Note
$\sigma = \frac{\sqrt{\varepsilon_r}}{120\pi l}\left(\frac{2V_0}{V_f}-1\right)$	Giese and Tiemann (1975)	V_0, V_f
$\sigma = \frac{\sqrt{\varepsilon_r}}{120\pi l}\left(\frac{V_1}{V_2-V_1}\right)$	Dalton *et al.* (1984)	V_1, V_2
$\sigma = \frac{\sqrt{\varepsilon_r}}{120\pi l}\left(\frac{V_1(2V_0-V_1)}{V_0(V_2-V_1)}\right)$	Topp *et al*. (1988)	V_0, V_1, V_2

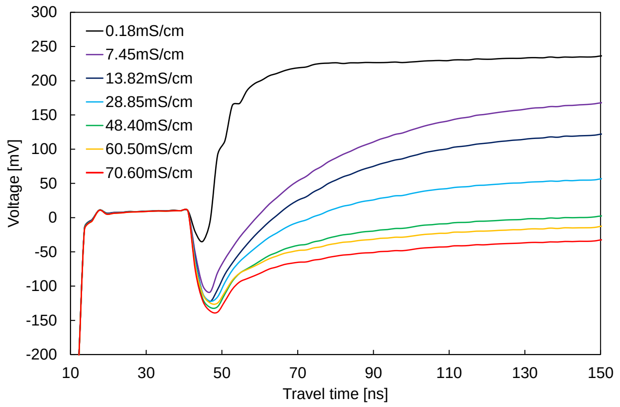


Fig. 9 Electromagnetic signals from optimized TDR probe in water with various salinities

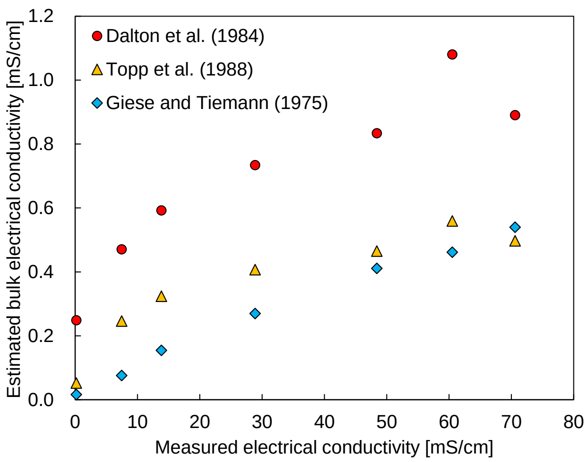


Fig. 10 Estimated electrical conductivity from suggested equations versus measured electrical conductivity

Giese and Tiemann (1975) particularly considers V_f, and it predominantly reflects the characteristics of electrical conductivity rather than other values of V_x.

For verification, the optimized TDR probe was penetrated into soils under water with 3% salinity, and the copper concentration varied from 0 mg/L to 10 mg/L. As the volumetric water content of soil affects to the signal of electromagnetic waves, the relative density of soils should be consistent. Thus, soils are settled by using the water pluviation method for consistency of relative density. The electromagnetic signals are shown in Fig. 11. Fig. 11 shows that the voltage decreased as the copper concentration

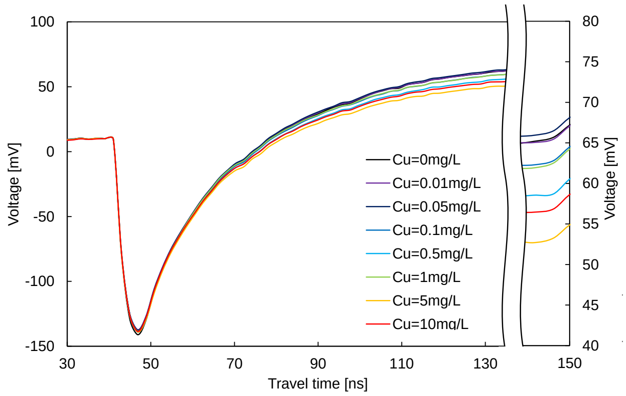


Fig. 11 Electromagnetic signals from optimized TDR probe penetrated into the simulated seabed

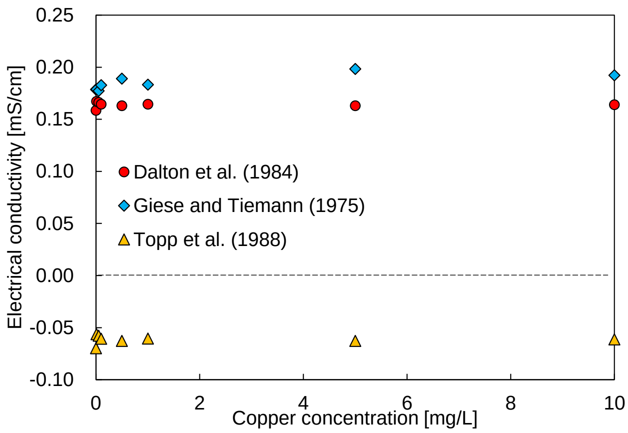


Fig. 12 Estimated electrical conductivity from suggested equations with respect to copper concentration

increased, similar to the experimental results in Figs. 3 and 5. The electrical conductivities were estimated using the equations in Table 1 and are plotted in Fig. 12. Fig. 12 shows that the electrical conductivity estimated by Topp *et al.* (1988) fails to assess the contaminant owing to negative values. Furthermore, the electrical conductivity estimated by Dalton and Van Genuchten (1986) is almost constant and is randomly distributed at low copper concentrations. However, the electrical conductivity from Giese and Tiemann (1975) profitably captures various contaminants, which are simulated by different copper concentrations. Consequently, a TDR probe with seven electrodes coated with varnish was optimized through an experimental study, and V_f should be considered for the estimation of reliable electrical conductivity. Further study on the effect of other contaminant types and probe shapes regarding penetration capacity is recommended for practical use in marine field.

5. Conclusions

The objective of this study was to evaluate the influence of coating materials and the number of electrodes used to optimize a TDR probe to detect contaminants in saline soil. Coating materials of epoxy, top-coat, and varnish were prepared, and two, three, four, and seven electrodes were designed. Three percent salinity water was prepared to simulate the ocean environment, and copper concentrations varied from 0 to 10 mg/L to grade the contaminants. Electromagnetic signals from the TDR probes were received and analyzed to select the optimized TDR probe. Then, the optimized TDR probe penetrated the soils that simulated the ocean sediments for verification. The following observations were made from this experimental study:

- Single-coated epoxy was limited at high copper concentrations owing to the short circuit caused by increased conductance of the material's characteristics. Meanwhile, the double-coated epoxy was restricted to a low copper concentration because of the massive coating thickness, which restricted the invasion of aggressive ions. The varnish gradually and continuously captured the increase in copper concentration, while the top-coat became insensitive at high copper concentrations owing to the high impedance of the materials.
- Time domain reflectometry probe with two electrodes exhibited unstable electromagnetic signals, which resulted from the noise and loss of wave signals. Thereafter, the three electrodes produced relatively stable signals, although the difference between the final converged voltages grew narrower. Then, TDR probes with four and seven electrodes exhibited more stable and distinct electromagnetic signals. Additionally, more electrodes can sample a concentrated soil volume around the center electrode, which is desirable for routine measurements.
- From the calculations of the electrical conductivities from the suggested equations, the equation regarding the voltage at the travel time of 150 ns successfully captured the different contaminants, which were simulated by different copper concentrations. Consequently, the case of seven electrodes coated with varnish was determined as the optimized TDR probe through an experimental study, and the voltage at the travel time of 150 ns was used for the reliable estimation of contaminants in the saline soil. In addition, the influence of field conditions such as water salinity and temperature and long-term performance should be assessed to extend the applicability of this fundamental research.

Acknowledgments

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