Reliability-based remediation control for contaminated groundwater

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ABSTRACT

Worldwide, many people depend on groundwater for daily drinking water. Groundwater contamination is being increasingly reported in recent years. The development of a rational remediation method is an important subject in geo-environmental engineering. This research project aims to develop a reliability-based remediation method for the pump-and-treat method, which is the most popular remediation method for contaminated groundwater. In this paper, the general concept of the proposed method and the reliability analysis method for determining the remediation target are explained, and the usefulness of the proposed method is discussed based on three-dimensional numerical simulation results.

Keywords: reliability, remediation, groundwater, risk.

1 INTRODUCTION

Groundwater contamination is being increasingly reported in recent years. The development of a rational remediation method is an important subject in geo-environmental engineering. This research project aims to develop a reliability-based remediation method for the pump-and-treat method, which is the most popular remediation method for contaminated groundwater. In this paper, the general concept of the proposed method and the reliability analysis method for determining the remediation target are explained, and the usefulness of the proposed method is discussed based on three-dimensional numerical simulation results.

2 BASIC CONCEPT OF THE PROPOSED REMEDIATION

In the pump-and-treat method, contaminated groundwater is extracted using the remediation well, and the contaminant concentration is reduced to an acceptable limit, after which the treated water is re-injected into the aquifer. Generally, multiple wells

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are installed at the remediation site, and they are controlled by expert engineers. Groundwater contamination problems are site-specific and contaminant-specific. Therefore, in order for the remediation to be successful, it is important to control the well by using monitoring data. The authors of this article have investigated this problem. Hata et al. (2010) proposed the fuzzy inference model (Ex., Harris, 2000) for rational control of the remediation work. Miyata et al. (2013) demonstrated the usefulness of the application of information-communication technology for remediation work. The concept of the author’s proposed method is shown in Figures 1 and 2. In the method, remediation wells are controlled based on decision support analysis using the fuzzy model. The fuzzy analysis considers three site conditions: contaminant concentration, the pumping rate of the remediation well, and the groundwater level. This method is expected to enable more reliable, economical, and speedy remediation.

3 DETERMINATION OF THE REMEDIATION TARGET BASED ON RELIABILITY ANALYSIS

In the fuzzy analysis, the next remediation condition is decided by using the membership functions. Figure 3 illustrates important parameters in the membership functions. Both $X_{\text{max}}$ and $X_{\text{min}}$ can be determined from the control range. $X_{a-1}$ or $X_{a-2}$ and $X_{b-1}$ or $X_{b-2}$ can be determined as the output from the fuzzy analysis is smooth. $X_T$ is the most important parameter, and it may be closely related to the remediation target. Here, determination of $X_T$ with reliability theory is discussed.

At the remediation site, the soil property and contamination condition are not homogeneous. However, the number of site investigations that can be performed is limited. It is very difficult to capture actual and complicated groundwater behavior. Thus the uncertainty in the remediation work should be taken into account when determining the membership function. Figures 4(a) and 4(b) illustrate the effect of pumping up groundwater under the assumption that the contaminant concentration, $C$, and the change in groundwater height, $\Delta H$, can be statistically treated. In this figure, $C$ and $\Delta H$ are assumed to be random variables with a normal distribution ($\mu$ denotes average and COV denotes
coefficient of variation). Upon pumping up the groundwater, the distribution of $C$ moves toward the left because the concentration decreases, and the exceedance probability, $P_e(C)$, that $C$ is higher than the allowable limit, $C_a$, decreases, as shown Figure 4(a). Considering that the objective of remediation is to reduce the allowable limit of $P_e(C)$, it is reasonable to select $\mu_C$ as $X_T$. A similar consideration can be applied with regard to the changing groundwater level. Upon pumping up the groundwater, the distribution of $\Delta H$ moves toward the right because the groundwater level decreases, and the probability, $P_e(\Delta H)$, that the observed $\Delta H$ is larger than the allowable limit, $\Delta H_a$, increases, as shown Figure 4(b). Considering that the objective of remediation is to reduce the allowable limit of $P_e(\Delta H)$, it is reasonable to select $\mu_{\Delta H}$ as $X_T$.

From the above discussion, if the exceedance probability, $P_e$, the allowable limits, $C_a$ or $\Delta H_a$, and the remediation target, $X_T$, are shown by an explicit equation, the determination of $X_T$ becomes simple. In this section, a simple equation to show their relation is formulated by using basic reliability theory. The exceedance probability, $P_e$, that the observed value, $X$, exceeds an allowable value, $X_a$, can be shown by the following cumulative density function:

$$P_e = \int_{-\infty}^{X_a} f(X) \, dX$$

(1)

$f(X)$ is a probability density function. In this study, $f(X)$ is assumed to be a normal distribution function, representing the simplest function. By using William’s approximation (Williams, 1946), $P_e$ can be shown as follows:

$$P_e = 0.5 \left[ 1 + \sqrt{1 - \exp(-2 z_e/\pi)} \right]$$

(2)

where $z_e$ is shown by eq. (3), $\mu_x$ is the average of $X$, and $\sigma_x$ is the standard deviation of $X$.

$$z_e = (X - \mu_x)/\sigma_x$$

(3)

From eq. (2), $z_e$ can be shown as a function of $P_e$.

$$z_e(P_e) = \sqrt{(\pi/2) \log \left\{ 4 P_e(1 - P_e) \right\}}$$

(4)

Using eqs. (3) and (4), the ratio of $X_T$ to $X_a$ can be shown explicitly by using the following equation:

$$X_T/X_a = \left\{ 1 + z_e(P_e) \text{COV}_x \right\}^{-1}$$

(5)

By using this equation, the remediation target $X_T$ can be determined easily by considering the allowable exceedance probability and variance of the remediation target.

4 NUMERICAL INVESTIGATION

It is preferable to verify the effectiveness of the proposed system at actual sites. However, the problem focused on in this study was likely to adversely affect people’s health and to involve a certain financial cost. Therefore, in this research, contaminated ground was reproduced numerically based on data from actual remediation sites, and numerical simulations were performed for verification. For the numerical simulation, three-dimensional convective diffusion analyses were performed.

In a series of numerical investigations, first the pumping rate was calculated for each well via decision support analysis using the contaminant concentration, groundwater level, and pumping rate of the initial condition. In this study, fuzzy and proportional-integral-derivative (PID) control methods were used in the investigation. Next, the calculated pumping rate was reflected in the boundary conditions of each well. In the next investigation, the contaminant concentration, groundwater level, and pumping rate were calculated using three-dimensional convective diffusion analysis. The above two steps were repeated.

Figure 5 shows the plan of the remediation site discussed in this paper. Figure 6 shows a cross section. The maximum trichloroethylene (TCE) concentration was 0.52 mg/L. This was ~1.7 times the value specified in Japanese effluent standards (0.3 mg/L) and ~17 times that specified in Japanese environmental standards.
At this remediation site, three of the remediation wells had been installed up to depths of 13 m. Remediation continued for 1 year with the pump-and-treat method. The remediation wells were controlled empirically by an expert engineer. The remediation was considered complete when the TCE concentration was reduced to 0.15 mg/L. Numerical parameters were determined through calculations so that the calculated concentration-time relationship would be the same as the observed one. Table 1 shows the estimated numerical parameters.

A key issue of the proposed method is determining the important parameters $X_T$ shown in Figure 3. In particular, $\Delta H_T$ as $X_T$ for the groundwater level change and $C_T$ as $X_T$ for the contaminant concentration should be determined using eq. (5). In the present study, $\Delta H_T$ is evaluated by eq. (6), and ground settlement, $S_a$, which is caused by changes in the groundwater level, can be shown by eq. (7).

$$\Delta H_T = \frac{2S_a}{m_s H \gamma_w \Delta H / 2} \left(1 + z_s \left(P_e \right) \text{COV}_S \right)$$ (6)

$$S_a = m_s H \gamma_w \Delta H / 2$$ (7)

where $m_s$ is the coefficient of volume change, $H$ is the height of the consolidation layer, $\gamma_w$ is the unit weight of groundwater, and $\Delta H$ is the change in groundwater.

In the above equation, the change in effective stress, $\Delta P$, is assumed to be given by $\Delta P = \gamma_w \Delta H / 2$, and $S_a$ denotes the allowable settlement. In the present analysis, the pumping rate is determined so as to ensure that $\Delta H$ will not exceed $\Delta H_T$. $\Delta H_T - P_e$ relations calculated from eq. (6) are shown in Figure 7. In this study, $P_e = 10^{-5}$ and $\text{COV}_S = 0.4$ are assumed in the trial analysis. Finally, $\Delta H_T$ is determined to be 1.3 m. For $C_T$, $C_T - P_e$ relations calculated from eq. (5) are shown in Figure 8. The WHO (2001) stated that the allowable limit for water quality is $10^{-6} - 10^{-5}$. In this study, therefore, it was assumed that $P_e = 10^{-5}$, $\text{COV}_c = 0.2$ was assumed in the trial analysis. Finally, $C_T$ is determined to be 0.13 mg/L. By using the above parameters for the membership function, a series of numerical simulations were performed to investigate the effectiveness of the proposed method. Figure 9 shows the relationship between the TCE concentration, $C_{TCE}$, and the total pumped quantity, $V_p$. In fuzzy control, this relationship is linear, implying that fuzzy control is performed efficiently over the entire remediation period. In PID control, the pumped quantity was much higher in the final stage to reduce $C_{TCE}$ from 0.3 to 0.2 mg/L. The engineer’s empirical control was not efficient from the start of remediation.

Table 1. Parameters for numerical simulation.

| Layer name | Sand 1 | Loam | Sand 2 | Coarse sand |
|------------|--------|------|--------|-------------|
| Depth (m)  | 0 – 2.0| 2.0 – 5.0| 5.0 – 14.0| 14.0 – |
| Permeability, k (m/s) | $4.6 \times 10^{-5}$ | $8.5 \times 10^{-6}$ | $4.6 \times 10^{-5}$ | $1.4 \times 10^{-4}$ |
| Specific storage, $S_s$ (1/m) | $4.6 \times 10^{-7}$ | $1.8 \times 10^{-4}$ | $4.6 \times 10^{-5}$ | $9.4 \times 10^{-5}$ |
| Porosity, $\theta$ (%) | 40 | 50 | 40 | 35 |
| Effective porosity, $n_e$ (%) | 20 | 20 | 20 | 15 |

Figure 7. TCE concentration and cancer risk.
Hata et al. (2010) proposed an evaluation method for cancer risk from the observed TCE concentration based on ASTM E2081 (2000), which is often referred to as the RBCA model. This method is useful for notifying citizens of the risk involved. The cancer risk can be evaluated by the following equation:

\[
R_c = \frac{S_f I_w E_d E_f C_{TCE}}{B_w T_c 365 \text{(days/year)}}
\]  

where \(S_f\) is the slope factor \([\text{mg/kg-day}]^{-1}\), \(I_w\) is the daily water ingestion rate (L/day), \(E_d\) is the exposure duration (years), \(E_f\) is the exposure frequency (days/year), \(C\) is the TCE concentration (mg/L), \(B_w\) is the body weight (kg), and \(T_c\) is the carcinogen averaging time (years). Figure 10 shows the cancer risk evaluated from the observed TCE concentration during the remediation period. In this figure, the target cancer risk is also shown. The result of well 1 shows that the cancer risk is lower than the target risk after around 180 days. Next, the results of wells 2 and 3 show that the estimated risk is much lower than the target risk during the remediation period. The proposed model is therefore useful to provide information about the cancer risk to citizens during or after remediation work. With regard to the ground settlement risk caused by excess pumping of groundwater, a new index, \(R_s\), is proposed in this section.

\[
R_s = 1 - \left( \frac{\Delta H_f - \Delta H}{\Delta H_f} \right)
\]  

where \(\Delta H_f\) is the change in groundwater level before remediation, and \(\Delta H\) is the change in groundwater level after remediation.
5 SUMMARY

The main conclusions of this paper are as follows:
1. The basic concept of reliability-based remediation control is presented for the pump-and-treat method of contaminated groundwater. The proposed method controls the remediation wells by considering an exceedance probability that the contaminant concentration is higher than an allowable level, and that the changing groundwater level is higher than an allowable level.
2. The determination method of the membership functions used in the fuzzy analysis is shown. A simple equation formulated from basic reliability theory can be used to fix the membership functions easily.
3. The effectiveness of the proposed method was assessed via numerical simulations. The simulation results suggest that the proposed method could reduce the pumped quantity compared to PID control or an engineer’s empirical knowledge. Analysis results are also shown for cancer risks from contaminants and ground settlement risks due to excess pumping up of groundwater.

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