

## PERFORMANCE EVALUATIONS OF PUMP-AND-TREAT SYSTEM USING ADVECTION-DISPERSION ANALYSIS: EFFECTS OF CLAY LAYER ON REMEDIATION DURATION

HIROYUKI ISHIMORI<sup>i)</sup>, TAKESHI KATSUMI<sup>ii)</sup>, MASAMI YOSHIKAWA<sup>iii)</sup> and RYOICHI FUKAGAWA<sup>iv)</sup>

### ABSTRACT

To evaluate the effects of a clay layer on the performance of pump-and-treat remediation, an advection-dispersion analysis assuming non-sorption was calculated by changing five parametric variables, namely, the length of the clay layer, the thickness of the clay layer, the hydraulic conductivity of the clay layer, the effective molecular diffusion coefficient of the contaminants, and the contamination duration. The simulation procedure consisted of firstly contaminating the analysis domain, and then cleaning up this contaminated domain by a pump-and-treat system in order to consider strictly the contamination conditions of a clay layer at a real contaminated site. From the calculation results, the pump-and-treat remediation was found to be effective if at least one of the following two conditions was satisfied, namely, the hydraulic conductivity of the clay layer was greater than  $5.0 \times 10^{-5}$  cm/s or the thickness of the clay layer was less than 3 m. In addition, the contamination duration was an important parameter in evaluating the applicability of this pump-and-treat remediation to contaminated sites. For cases in which the contamination duration was short, the contamination conditions of the clay layer easily became heterogeneous such that the remediation duration was much longer than the contamination duration. It is necessary to note that contaminated sites may not always be remedied in a short period of time, even if the sites are discovered early.

**Key words:** advection-dispersion analysis, clay layer, contamination duration, groundwater contamination, pump-and-treat remediation (IGC: E7)

### INTRODUCTION

Pump-and-treat is one of the most widely used groundwater remediation technologies for groundwater that has been contaminated with chemicals such as chromate, trichloroethylene, and so on (Mackay and Cherry, 1989). This remediation system consists of flushing the contaminants from an aquifer by a groundwater flow enhanced through the pumping and the collecting of the contaminants in a pumping well. One of the advantages of this system is its ability to remove contaminants directly from a highly concentrated zone. In addition, pump-and-treat remediation is easy to apply because the installation of the equipment is relatively simple and the initial costs are low. Under certain conditions, however, a long-term operation may be required. This is because the removal of the contaminants becomes more and more difficult as the time since the pump-and-treat remediation was started grows longer. In a heterogeneous aquifer, particularly one which includes a clay layer, it is difficult

to flush out the contaminants in the clay layer with a groundwater flow. In general, the flow velocity through a clay layer is very low, and it is not enhanced much by pumping because the hydraulic conductivity of clay is much lower than that of sand. Under such a small groundwater flow, the contaminants in the clay layer cannot be flushed efficiently. Thus, a long operating duration and its associated costs are required in order to decrease the concentration of contaminated groundwater to the remediation target level (EPA, 1996; Cohen et al., 1997). To prevent this problem, it is necessary to evaluate the applicability of pump-and-treat remediation to each contaminated site.

To evaluate the applicability of pump-and-treat remediation to a contaminated site, it is important to clarify the characteristics of the soil, the contaminants, and the hydrogeology, for example, (1) the nature, the extent, and the distribution of the contaminants in the source area and the plumes, (2) the potential receptors and the risks posed by the contaminated groundwater,

<sup>i)</sup> Graduate Student, Department of Civil Engineering, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan.

<sup>ii)</sup> Associate Professor, Graduate School of Global Environmental Studies, Kyoto University, Sakyo, Kyoto 606-8501, Japan (tkatsumi@mbox.kudpc.kyoto-u.ac.jp).

<sup>iii)</sup> Graduate Student, ditto.

<sup>iv)</sup> Professor, Department of Civil Engineering, Ritsumeikan University, Kusatsu, Shiga 525-8577, Japan.

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and (3) the hydrogeologic and the contaminant properties. If all the characteristics are clarified in a primary investigation, the applicability to a contaminated site may be evaluated theoretically. However, it is impossible to obtain the characteristics in detail, because of the heterogeneities at a real site. Thus, it is important to evaluate this applicability with represented characteristics at sampling points in the primary investigation, considering changes in the observed concentration of contaminated groundwater with time at a monitoring well. Even if there are unknown characteristics that cannot be clarified in the primary investigation, the effects of these characteristics may appear in the observed concentration of contaminated groundwater at the monitoring well. It is possible to effectively judge whether to continue pump-and-treat remediation or to change to another remediation technology from the characteristic relation between the represented physical (hydrogeologic and contaminant) properties and the changes in the observed concentration of contaminated groundwater with time at the monitoring well. Knowledge of the changes in the observed concentration of contaminated groundwater with time at the monitoring well is useful for a site characterization; it becomes important information for guessing the unknown characteristics.

The purpose of this study was to evaluate the effects of a clay layer on pump-and-treat remediation technology. The effects were discussed from the following three viewpoints: (1) an investigation of the contamination mechanism and the remediation mechanism in the clay layer, (2) the effects of the clay layer on the characteristics of the observed concentration of contaminated groundwater at a monitoring well, and (3) the effects of the clay layer on the remediation duration required to remedy the contaminated groundwater to the remediation target level. These three points were evaluated using seepage and an advection-dispersion numerical analysis in a cross-sectional coordinate system. In the analysis, two processes were simulated, namely, an aquifer was firstly contaminated and then it was cleaned up by pump-and-treat remediation. Trichloroethylene dissolved in water was assumed as the contaminant. Its non-sorption to soils was assumed in order to provide a conservative evaluation; the contaminant was able to move easily through the groundwater and could not be caught in the clay layer under the assumed condition of non-sorption.

## BACKGROUND

It is well known that the amount of contaminants removed is drastically decreased in the range of a low concentration level for aquifers which include a clay layer, as shown in Fig. 1. This phenomenon is called the tailing phenomenon. It is reported that the tailing phenomenon is caused by the following: (1) the effects of the desorption of the contaminants and (2) the effects of the matrix diffusion (Keely, 1989; Palmer and Fish, 1992).

The first reason, the effects of the desorption of the

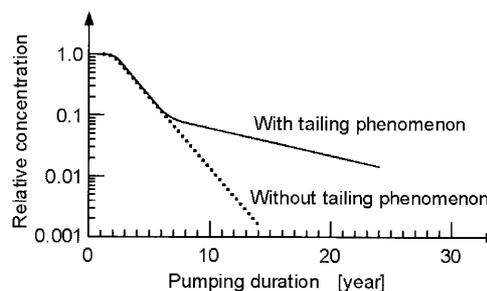


Fig. 1. Concentration profiles at the monitoring well during pump-and-treat remediation (Dash line: homogeneous sand aquifer without the tailing phenomenon, Solid line: heterogeneous aquifer including a clay layer with the tailing phenomenon)

contaminants, can be described as follows. Contaminants infiltrate a site flow through groundwater with sorption to subsurface media. Sorption acts to prevent the expansion of the contaminated plume. Thus, it provides a conservative evaluation if sorption is not considered when predicting the expansion of the contaminated plume. In contrast, desorption is important when predicting the removal of the contaminated plume, for example, in evaluating the amount of contaminants removed by pump-and-treat remediation. Even if contaminants in the void of the media are flushed by the pump-and-treat system, the contaminants sorbed to the subsurface media desorb from the matrix and dissolve in the groundwater. The effects of desorption appear significantly in the range of a low concentration level, so that sorption/desorption is generally reported as one of the reasons for the tailing phenomenon. Note that desorption is not caused without sorption. However, it may be impossible to evaluate the effects of sorption/desorption on the tailing phenomenon even with the most widely used mathematical theory which employs a non-hysteric equilibrium linear sorption model. In discussing the effects of sorption/desorption on the tailing phenomenon, the hysteric sorption (Swanson and Dutt, 1973) and the nonlinearity of the sorption isotherm (Berglund, 1995) are important. The former is important because the speed of the chemical reaction of desorption is larger than the speed of the chemical reaction of sorption (Kuo and Lotse, 1974), and the latter is important because the slope of the sorption isotherm in the range of a low concentration level is larger than that in the range of a high concentration level (Fetter, 1999). It may be difficult to evaluate the effects of sorption/desorption on the tailing phenomenon, because there have not yet been many reports on the applicability of a mathematical theory which can consider sorption/desorption in environmental geotechnical problems.

The second reason, the effects of the matrix diffusion, is described as follows. As contaminants advance through relatively permeable pathways in heterogeneous media, the concentration gradient is generated between media with different permeability levels. The concentration gradient causes a diffusion of the contaminants into less permeable media, so that it disperses the contami-

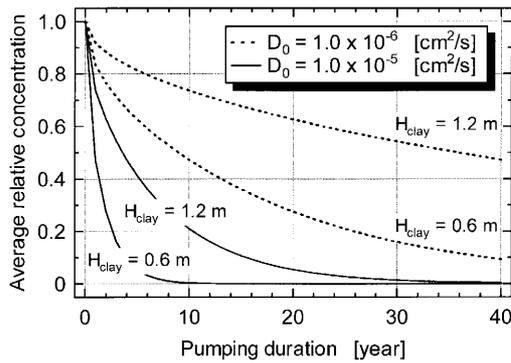


Fig. 2. Effects of the molecular diffusion coefficient and the thickness of the clay layer on the average decrease in relative concentration in the clay layer during pump-and-treat remediation

nated plume in the direction of the groundwater flow (Gillham et al., 1984) and retards the transport of some contaminants. Furthermore, in operating pump-and-treat remediation, contaminants in the relatively permeable zones may be flushed quickly relative to the contaminants in the less permeable zones. This causes the contaminants in the less permeable zones, which already had been contaminated, to diffuse slowly to the fresh zones flushed by pump-and-treat remediation. Thus, contaminants are continuously detected for a long term at the monitoring well installed in the downstream of the contaminated site. The effects of the matrix diffusion on the tailing phenomenon depend on the diffusion coefficient of the contaminants and the thickness of the less permeable media, namely, the clay layer. The effects of these parameters can be approximately evaluated by an analytical solution which assumes a one-dimensional diffusion out of the clay layer (Carslaw and Jaeger, 1986). If a clay layer with a thickness of  $H_{\text{clay}}$  is contaminated with a uniform initial concentration of  $c_0$  and a low concentration is maintained in the sand aquifer around the clay layer by pump-and-treat remediation, then the average relative concentration in the clay layer,  $c/c_0$ , is calculated by;

$$\frac{c}{c_0} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{D_0}{\tau R H_{\text{clay}}^2} (2n+1)^2 \pi^2 t\right) \quad (1)$$

where  $R$  [—] is the retardation factor,  $\tau$  [—] is the tortuosity,  $D_0$  [ $\text{L}^2/\text{T}$ ] is the free liquid molecular diffusion coefficient, and  $t$  [ $\text{T}$ ] is the time. This solution can easily be used to estimate the time required to remove the contaminants from a clay layer, as shown in Fig. 2. However, it is necessary to note that it may not be possible to use this solution when there is a heterogeneous contaminated clay layer, for example, in cases for which the contamination duration is short or the thickness of the clay layer is large. In the above cases, the clay layer would be contaminated heterogeneously, i.e., the interface between the sand aquifer and the clay layer is contaminated in high concentration, but the center of the clay layer is not contaminated as seriously as the interface because of the low permeability of the clay layer. If the

heterogeneous contamination conditions of the clay layer are neglected, the time required to remove the contaminants from the clay layer may be estimated lightly so that the performance of pump-and-treat remediation may be evaluated excessively. This is because contaminants in contaminated homogeneous media diffuse out more easily than those in contaminated heterogeneous media.

In this paper, the effects of the matrix diffusion on the tailing phenomenon are investigated in detail by a numerical analysis which considers the clay layer to be contaminated heterogeneously with time, not assuming the clay layer to be contaminated uniformly. The original purpose of this paper is to evaluate strictly the effects of a clay layer on the performance of pump-and-treat remediation by a numerical analysis which connects the contamination stage with the remediation stage. However, using this simulation procedure, it is possible to evaluate not only the effects of the clay layer, but also the effects of the contamination duration in relation to the remediation duration by pump-and-treat remediation.

## METHODS

### Governing Equations

The transport of the contaminants dissolved in the water phase can be described by an advection-dispersion equation, namely,

$$R \frac{\partial c}{\partial t} + v_i \frac{\partial c}{\partial x_i} - \frac{\partial}{\partial x_i} \left( D_{ij} \frac{\partial c}{\partial x_j} \right) = 0 \quad (2)$$

where subscripts  $i$  and  $j$  indicate the free index and the dummy index for the tensor notation, respectively,  $c$  [ $\text{M}/\text{L}^3$ ] is the concentration of contaminants in the water phase,  $R$  [—] is the retardation factor,  $D_{ij}$  [ $\text{L}^2/\text{T}$ ] is the hydrodynamic dispersion tensor, and  $v_i$  [ $\text{L}/\text{T}$ ] is the pore velocity. The retardation factor is represented as  $R = 1 + \rho_d K_d / \phi$ , where  $\phi$  [—] is the porosity,  $\rho_d$  [ $\text{M}/\text{L}^3$ ] is the dry bulk density of the soil, and  $K_d$  [ $\text{L}^3/\text{M}$ ] is the partition coefficient. In this paper, partition coefficient  $K_d$  was assumed to be zero. For isotropic porous media, the hydrodynamic dispersion tensor is represented as  $D_{ij} = \alpha_T v \delta_{ij} + (\alpha_L - \alpha_T) v_i v_j / v + D_e \delta_{ij}$  (Bear, 1972), where  $\alpha_L$  [ $\text{L}$ ] is the longitudinal dispersivity,  $\alpha_T$  [ $\text{L}$ ] is the transverse dispersivity, and  $D_e$  [ $\text{L}^2/\text{T}$ ] is the effective molecular diffusion coefficient for a contaminant dissolved in the water phase. Effective molecular diffusion coefficient  $D_e$ , in general, is defined by the product of tortuosity  $\tau$  [—] for a soil particle and free liquid molecular diffusion coefficient  $D_0$  [ $\text{L}^2/\text{T}$ ]. Dispersion tensor  $D_{ij}$  is described by its longitudinal and transverse principal components in directions parallel to and orthogonal to the flow line, respectively. Moreover, pore velocity  $v_i$  is defined as the value into which the darcy velocity,  $q_i$  [ $\text{L}/\text{T}$ ], is divided by the porosity,  $\phi$ , and is represented as  $v_i = q_i / \phi = -k_{ij} \partial H / \partial x_j / \phi$ , where  $H$  [ $\text{L}$ ] is the piezometric potential head in the water phase and  $k_{ij}$  [ $\text{L}/\text{T}$ ] is the hydraulic conductivity. For the evaluation of pore velocity  $v_i$ ,

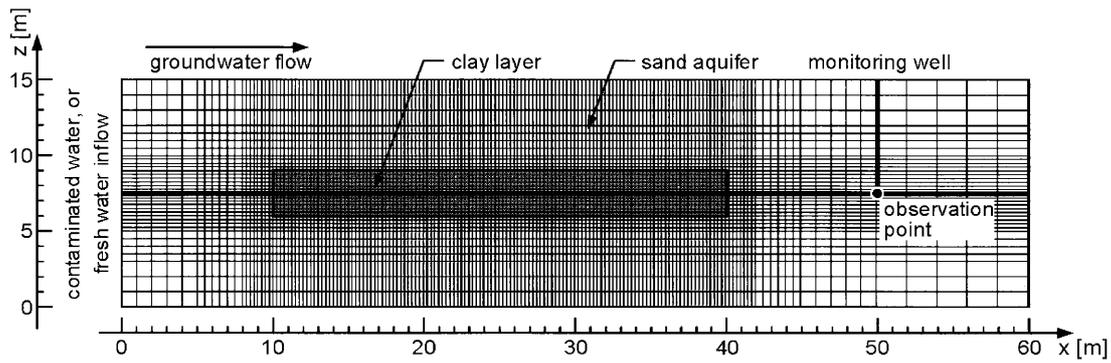


Fig. 3. Analysis domain and finite element mesh

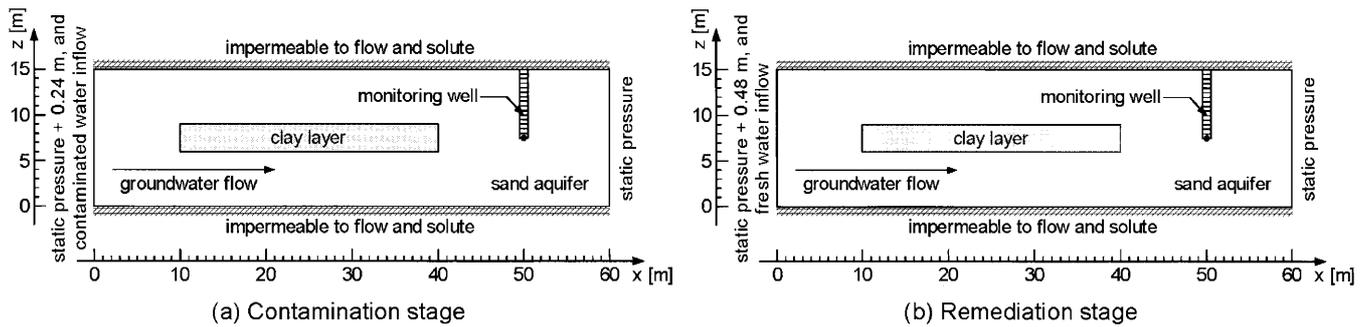


Fig. 4. Boundary conditions for the numerical simulations of contamination and remediation stages: (a) in the contamination stage, the groundwater which was contaminated by trichloroethylene infiltrated the analysis domain from the left boundary with a hydraulic gradient of  $i_{cont} = 1/250$  for the contamination duration of  $T_{cont}$  and (b) in the remediation stage, the fresh groundwater infiltrated the analysis domain contaminated in the contamination stage from the left boundary with a hydraulic gradient of  $i_{pump} = 1/125$  for 30 years

piezometric potential head  $H$  can be calculated from a seepage equation in the saturated aquifer, in other words,

$$\frac{\partial}{\partial x_i} \left( k_{ij} \frac{\partial H}{\partial x_j} \right) = 0 \tag{3}$$

where it is noted that the water is assumed not to be compressed.

*Numerical Model*

The advection-dispersion equation shown in Eq. (2) was numerically solved using the Eulerian-Lagrangian method (Neuman, 1984) with an implicit scheme for time discretization. The seepage equation shown in Eq. (3) was numerically solved using the finite element method.

The Eulerian-Lagrangian method can calculate, with stability and good accuracy, the advection-dispersion problem including characteristics of the parabolic equation and the hyperbolic equation. In this method, the advection-dispersion equation is divided into the advection equation and the dispersion equation. The advection equation was solved using the single step reverse particle tracking method, while the dispersion equation was solved using the finite element method. The code has been developed by the authors based on the procedure of numerical calculation using the Eulerian-Lagrangian method described in Neuman (1984).

*Simulation Procedure*

The advection-dispersion analysis was conducted for the cross-sectional analysis domain shown in Fig. 3. The analysis domain had a cross area of  $15 \times 60$  m and it was assumed to be a saturated aquifer with a clay layer. The groundwater flow was in the  $x$ -direction. The monitoring well was installed downstream of the clay layer. The finite element mesh was divided into the  $x$ -direction by  $\Delta x = 0.25 \sim 2.0$  m and into the  $z$ -direction by  $\Delta z = 0.1 \sim 1.0$  m. The number of total nodes was 6068 and the number of total elements was 5868.

The advection-dispersion analysis was calculated in two steps, namely, the aquifer was firstly contaminated and then it was cleaned up by pump-and-treat remediation. In the first step, called the contamination stage, the groundwater which was contaminated by trichloroethylene, infiltrated the analysis domain from the left boundary with a hydraulic gradient of  $i_{cont} = 1/250$  for a contamination duration of  $T_{cont}$ . The initial condition during the contamination stage in the analysis domain was a contaminated groundwater concentration of  $c = 0$  mg/L. The boundary condition in the contamination stage is shown in Fig. 4(a). For the seepage equation, the left-boundary value of piezometric potential head  $H$  was given as being 0.24 m larger than the right-boundary value of  $H$ . For the advection-dispersion equation, the left-boundary value of contaminated groundwater

concentration  $c$  was given as 1100 mg/L; this was the aqueous solubility of the trichloroethylene. In the second step, called the remediation stage, fresh groundwater was infiltrated from the left boundary to the analysis domain contaminated during the contamination stage with a hydraulic gradient of  $i_{\text{pump}} = 1/125$  for 30 years. The initial condition in the remediation stage consisted of the contaminated groundwater concentration profiles obtained from the contamination stage. The boundary condition in the remediation stage is shown in Fig. 4(b). For the seepage equation, the left-boundary value of piezometric potential head  $H$  was given as being 0.48 m larger than the right-boundary value of  $H$ . Pump-and-treat remediation was imitated by the enhanced groundwater flow that was larger than the groundwater flow during the contamination stage. For the advection-dispersion equation, the left-boundary value of the contaminated groundwater concentration  $c$  was given as being 0 mg/L that was imitated to be the fresh groundwater.

The soil and contaminant properties are shown in Table 1, and the simulation cases are shown in Table 2 in this analysis. These simulation cases were to evaluate effects of five parametric variables; (1) the thickness  $H_{\text{clay}}$  and the length  $L_{\text{clay}}$  for clay layer geometries, (2) the hydraulic conductivity  $k_{\text{clay}}$  of clay layer, (3) the effective molecular diffusion coefficient  $D_e$ , and (4) the contamination duration  $T_{\text{cont}}$ . The symbol  $K_r$  was the ratio of clay layer hydraulic conductivity to sand as  $K_r = k_{\text{clay}}/k_{\text{sand}}$ .

This analysis was conducted to discuss how much the

removal efficiency of the contaminants in the clay layer was declined due to the difference of hydraulic conductivity of the clay layer included in the aquifer. That is, this analysis focused on whether the tailing phenomenon was caused by the heterogeneity of aquifer-structure and the heterogeneous contamination distribution of clay layer without considering the effects of the adsorption/desorption phenomenon. The amount of the contaminants transporting from the clay layer to the sand aquifer would affect the occurrence of the tailing phenomenon.

**Table 1. Properties for the sand aquifer, the clay layer and the dissolved trichloroethylene (TCE) in the water phase**

Parameter	Unit	Value
Properties for sand aquifer and clay layer		
Hydraulic conductivity in sand aquifer, $k_{\text{sand}}$	cm/s	$5.0 \times 10^{-3}$
in clay layer, $k_{\text{clay}}$	cm/s	$K_r \times k_{\text{sand}}$
Effective porosity in sand aquifer, $\phi_{\text{sand}}$	—	0.30
in clay layer, $\phi_{\text{clay}}$	—	0.15
Dry bulk density in sand aquifer, $\rho_{\text{d,sand}}$	g/cm <sup>3</sup>	1.80
in clay layer, $\rho_{\text{d,clay}}$	g/cm <sup>3</sup>	1.80
Properties for dissolved TCE in water phase		
Longitudinal dispersivity, $\alpha_L$	m	10
Transverse dispersivity, $\alpha_T$	m	1
Effective molecular diffusion coefficient, $D_e$	cm <sup>2</sup> /s	$1.0 \times 10^{-6}$ , $1.0 \times 10^{-5}$
Partition coefficient, $K_d$	mL/g	0 <sup>†</sup>

<sup>†</sup>assumed non-adsorption and non-desorption.

**Table 2. Analysis conditions**

Case	$H_{\text{clay}}$ [m]	Clay layer $L_{\text{clay}}$ [m]	$K_r$	Contaminants $D_e$ [cm <sup>2</sup> /s]	Contamination duration $T_{\text{cont}}$ [year]
Effects of clay layer geometries					
H-1, L-10	1	10	0.00100	$1.0 \times 10^{-5}$	10.00
H-1, L-30	1	30	0.00100	$1.0 \times 10^{-5}$	10.00
H-3, L-10	3	10	0.00100	$1.0 \times 10^{-5}$	10.00
H-3, L-30	3	30	0.00100	$1.0 \times 10^{-5}$	10.00
Effects of clay layer hydraulic conductivity					
$K_r$ -0.00001	3	30	0.00001	$1.0 \times 10^{-5}$	10.00
$K_r$ -0.00010	3	30	0.00010	$1.0 \times 10^{-5}$	10.00
$K_r$ -0.00100	3	30	0.00100	$1.0 \times 10^{-5}$	10.00
$K_r$ -0.01000	3	30	0.01000	$1.0 \times 10^{-5}$	10.00
$K_r$ -0.10000	3	30	0.10000	$1.0 \times 10^{-5}$	10.00
$K_r$ -1.00000 (non-clay)	3	30	1.00000	$1.0 \times 10^{-5}$	10.00
Effects of effective molecular diffusion coefficient					
D-1.00E-06	3	30	0.00100	$1.0 \times 10^{-6}$	10.00
D-1.00E-05	3	30	0.00100	$1.0 \times 10^{-5}$	10.00
Effects of contamination duration					
T-5	3	30	0.00100	$1.0 \times 10^{-5}$	5.00
T-7.5	3	30	0.00100	$1.0 \times 10^{-5}$	7.50
T-10	3	30	0.00100	$1.0 \times 10^{-5}$	10.00
T-20	3	30	0.00100	$1.0 \times 10^{-5}$	20.00
T-30	3	30	0.00100	$1.0 \times 10^{-5}$	30.00

$H_{\text{clay}}$ : thickness of clay layer,  $L_{\text{clay}}$ : length of clay layer,  $K_r$ : ratio of clay layer hydraulic conductivity to sand ( $k_{\text{sand}} = 5.0 \times 10^{-3}$  cm/s), and  $D_e$ : effective molecular diffusion coefficient.

Therefore, the geometric condition and the hydraulic conductivity of clay layer, the diffusion coefficient, and the contamination duration were parametrically changed assuming the partition coefficient,  $K_d$ , to be zero. The geometric condition of the clay layer was parametrically changed within the large ranges as like  $H_{\text{clay}} \leq 3$  m and  $L_{\text{clay}} \leq 30$  m in order to clearly present the effects of the difference in hydraulic conductivity of the clay lense included in the aquifer. The thickness,  $H_{\text{clay}}$ , would affect the amount of the contaminants leaching from the clay layer by the diffusion, which is considered an important driving force in discussing the transport of the contaminants in the clay layer having much lower hydraulic conductivity. The amount of the solute transport by the diffusion was dependent on the concentration gradient generated across the boundary between the clay layer and the sand aquifer; that is, it was dependent on the thickness of the clay layer. If the thickness was larger, the time required to transport the contaminants in the clay layer to the sand aquifer becomes longer. As a result, the tailing phenomenon would occur in the remediation stage. Therefore, the thickness,  $H_{\text{clay}}$ , would be an important parameter in discussing removal efficiency of the contaminants from the aquifer and the applicability of the pump-and-treat remediation technology. Another geometric parameter  $L_{\text{clay}}$  was set into the limited length although a clay layer having the limited length may rarely exist in a real site. The reason assuming the limited length for  $L_{\text{clay}}$  is because it may be difficult to simulate the transport of the chemical compounds in the heterogeneous aquifer with the semi-infinite clay layer like a laminated ground by the finite element method. For this reason, the clay layer with the limited length was separated from the boundaries of the analysis domain. The dispersivity and the diffusion coefficient of the clay were assumed to be the same as those of the sand since this study intends to focus on the effect of variability of hydraulic conductivity. The value of the longitudinal dispersivity  $\alpha_L$  was determined according to the data reported by Spitz and Moreno (1996), considering the scale of the analysis domain. The value of the transverse dispersivity  $\alpha_T$  was set to about 1/10 of the longitudinal dispersivity  $\alpha_L$ , which is the value widely used. The diffusion coefficients of the organic compounds were  $1.0 \times 10^{-6}$  to  $1.0 \times 10^{-5}$  cm<sup>2</sup>/s (Cohen et al., 1997).

## RESULTS

### *Effects of the Clay Layer Geometries*

The effects of the clay layer geometries on the groundwater concentration at the monitoring well are shown in Fig. 5. This concentration profile was monitored at the point  $(x, z) = (50, 7.5)$  in the analysis domain (see Fig. 3). In this figure, the calculated concentration levels at the monitoring well are plotted for the remediation stage. The open plots show the results for a clay layer with a thickness of  $H_{\text{clay}} = 1$  m, while the closed plots show the results for a clay layer with a thickness of  $H_{\text{clay}} = 3$  m. The dash line shows the results for a case in which there is no

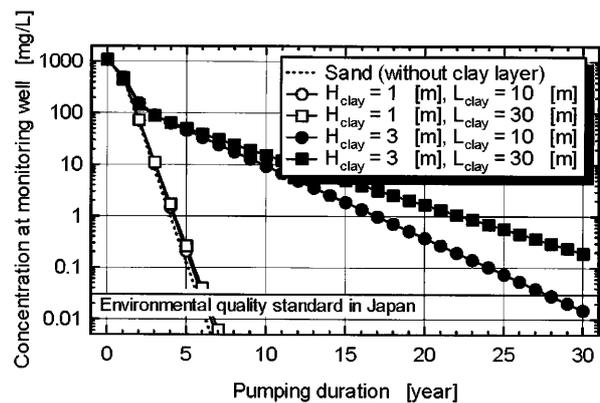


Fig. 5. Effects of the clay layer geometries on the concentration profiles at the monitoring well (HL-series):  $K_r = 0.001$ ,  $D_c = 1.0 \times 10^{-5}$  cm<sup>2</sup>/s and  $T_{\text{cont}} = 10$  years

clay layer; there was only a sand aquifer in the analysis domain. This case was simulated by setting the hydraulic conductivity of clay,  $k_{\text{clay}}$ , to be equal to that of sand,  $k_{\text{sand}}$ . The contamination duration,  $T_{\text{cont}}$ , was set at 10 years. In the contamination stage, the groundwater concentration at the monitoring well reached a maximum concentration of  $c = 1100$  mg/L, which was equal to the concentration value given at the upper boundary (left boundary of the analysis domain) about 2 years after the start of the contamination stage.

From Fig. 5, it is seen that the thickness of the clay layer was sensitive to the concentration profiles at the monitoring well. For the aquifer which included the clay layer with a small thickness of  $H_{\text{clay}} = 1$  m, it was easy to remove the contaminants and it was possible to decrease the concentration of contaminated groundwater to the remediation target level (the environmental quality standard of TCE in Japan is 0.03 mg/L) by pumping for a duration of 10 years. For the aquifer which included the clay layer with a large thickness of  $H_{\text{clay}} = 3$  m, however, it was difficult to remove the contaminants and it was impossible to decrease the concentration over a short period of time. The clay layer with the large thickness caused the tailing phenomenon. Tailing refers to the progressively slower rate of decline in a concentration of contaminated groundwater with the continued operation of the pump-and-treat system. Figures 6 and 7 show the concentration and the pore velocity levels in the remediation stage for the aquifers which included the clay layer with the small thickness of  $H_{\text{clay}} = 1$  m and the large thickness of  $H_{\text{clay}} = 3$  m, respectively. The efficiency of the removal of the contaminants in the clay layer was significantly different for these two conditions, although the flow velocity was almost the same. The contaminants in the clay layer with the small thickness of  $H_{\text{clay}} = 1$  m were removed quickly and the concentration of contaminated groundwater was decreased from the initial concentration of 1100 mg/L to 0.59 mg/L by pumping for a period of 5 years. This was because the transport of chemical compounds by diffusion was larger for the case of the small thickness of  $H_{\text{clay}} = 1$  m than for that of the

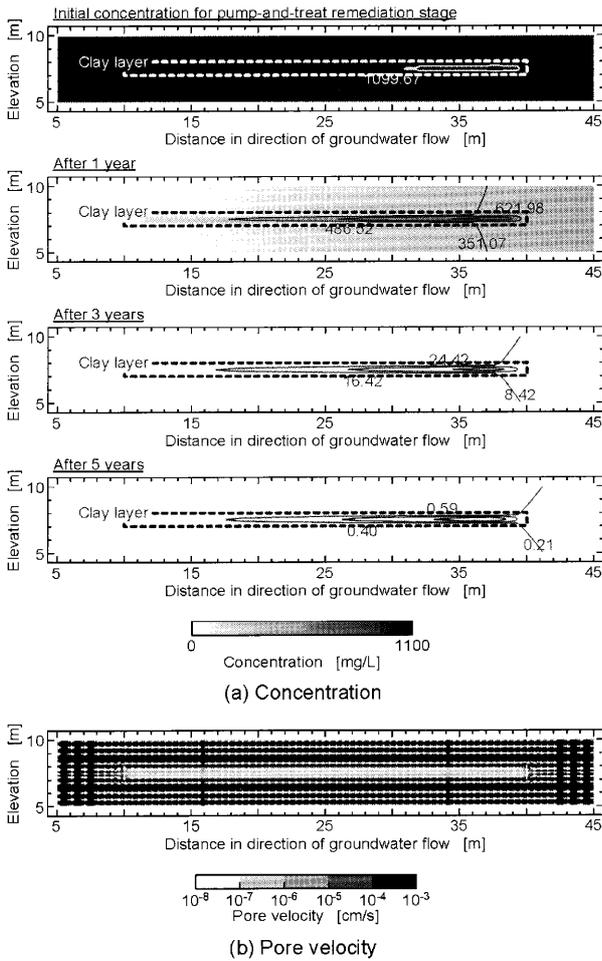


Fig. 6. Concentration and pore velocity in the remediation stage (case H-1, L-30):  $H_{\text{clay}} = 1 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$ ,  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$  and  $T_{\text{cont}} = 10 \text{ years}$

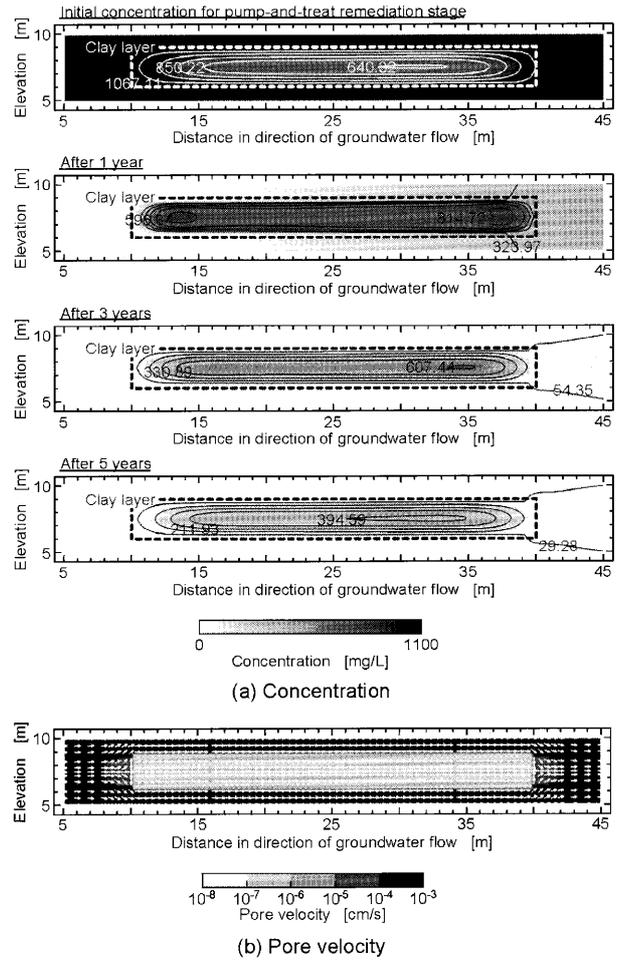


Fig. 7. Concentration and pore velocity in the remediation stage (case H-3, L-30):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$ ,  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$  and  $T_{\text{cont}} = 10 \text{ years}$

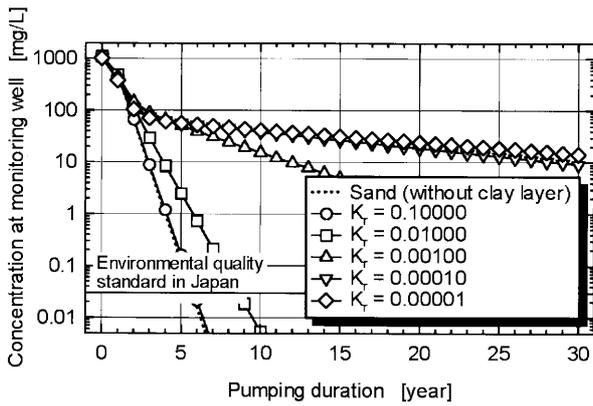
large thickness of  $H_{\text{clay}} = 3 \text{ m}$ . If pump-and-treat remediation is used for an aquifer with a clay layer, the groundwater will flow through relatively permeable media. Thus, the contaminants on the interface between the sand aquifer and the clay layer are flushed by the groundwater flow, even if it is impossible to remove the contaminants in the center of the clay layer. Consequently, the concentration of contaminants on the interface between the sand aquifer and the clay layer become low by flushing, while the concentration at the center of the clay layer remained high. The contaminants in the clay layer diffuse to the sand aquifer, because the concentration gradient is generated in the clay layer between the highly contaminated center of the clay layer and the lowly contaminated interface with the sand aquifer. The transport of chemical compounds to the sand aquifer by diffusion grows larger if the distance between the highly contaminated center of the clay layer and the lowly contaminated interface with the sand aquifer, the thickness of the clay layer, is smaller. Therefore, contaminants in the clay layer could be easily removed by a large diffusion effect without the tailing phenomenon in the case of the small thickness of  $H_{\text{clay}} = 1 \text{ m}$ . It is concluded that the thickness

of a clay layer has a significant effect on the removal efficiency. Contaminants in a clay layer with a small thickness can be removed in a short period of time.

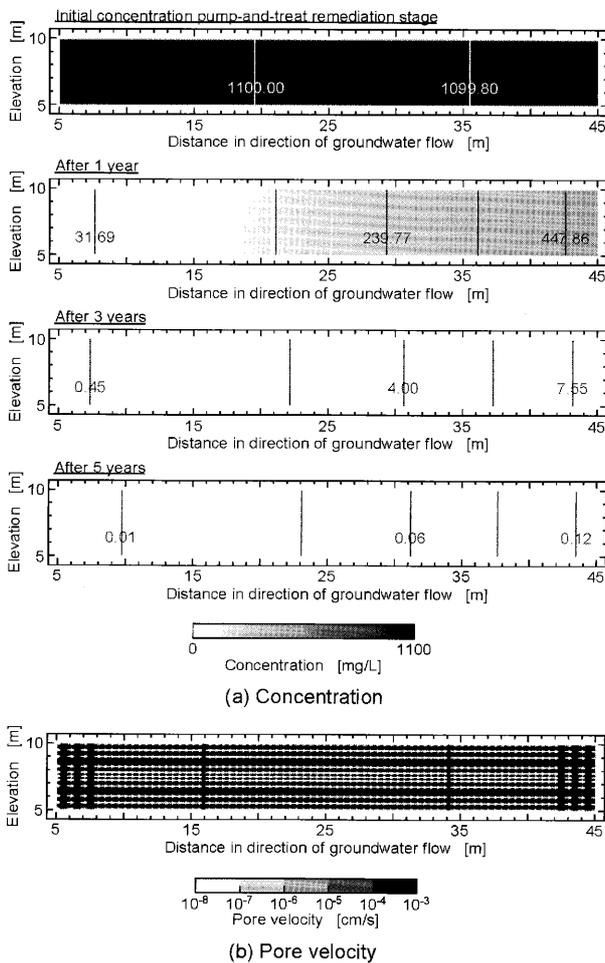
*Effects of the Hydraulic Conductivity of the Clay Layer*

The effects of the hydraulic conductivity of the clay layer on the concentration of contaminated groundwater at the monitoring well are shown in Fig. 8. In this figure, the calculated concentration levels at the monitoring well are plotted after pump-and-treat remediation was applied for a contaminated aquifer which included a clay layer with various hydraulic conductivity values. Symbol  $K_r$  was the ratio of the hydraulic conductivity of the clay layer to the hydraulic conductivity of the sand, namely,  $K_r = k_{\text{clay}}/k_{\text{sand}}$ , where  $k_{\text{sand}}$  was set as  $5.0 \times 10^{-3} \text{ cm/s}$ . The dash line shows the results for a case without a clay layer; there was only a sand aquifer in the analysis domain.

In the cases where hydraulic conductivity ratio  $K_r$  is greater than 0.01, the concentration of contaminated groundwater was decreased to the remediation target level as fast as pump-and-treat remediation was used for the homogeneous permeable sand aquifer. Contaminants could be removed in a short duration without the tailing

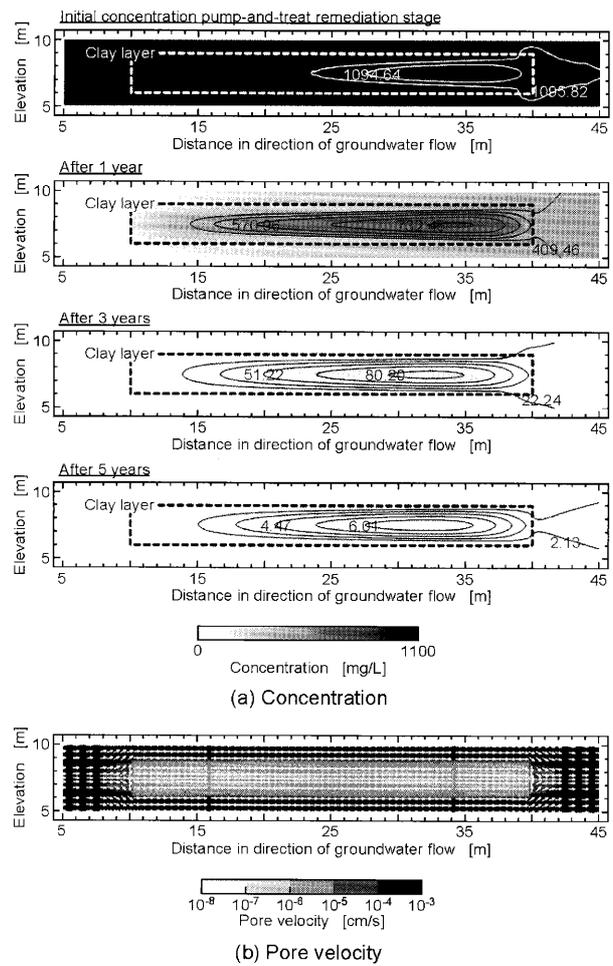


**Fig. 8.** Effects of the clay layer hydraulic conductivity on the concentration profiles at the monitoring well ( $K_r$ -series):  $H_{\text{clay}} = 3$  m,  $L_{\text{clay}} = 30$  m,  $D_e = 1.0 \times 10^{-5}$  cm<sup>2</sup>/s and  $T_{\text{cont}} = 10$  years



**Fig. 9.** Concentration and pore velocity in a homogeneous sand aquifer in the remediation stage (case  $K_r=1.00000$ ):  $D_e = 1.0 \times 10^{-5}$  cm<sup>2</sup>/s and  $T_{\text{cont}} = 10$  years

phenomenon. In the range from  $K_r=0.01$  to  $K_r=0.001$ , the concentration profiles were significantly different in the slope of the concentration versus the pumping duration. In the case of  $K_r=0.01$ , the slope of the concentration versus the pumping duration was so large that the contaminants were removed in a short duration. In



**Fig. 10.** Concentration and pore velocity in the remediation stage (case  $K_r=0.01000$ ):  $H_{\text{clay}} = 3$  m,  $L_{\text{clay}} = 30$  m,  $K_r=0.01$ ,  $D_e = 1.0 \times 10^{-5}$  cm<sup>2</sup>/s and  $T_{\text{cont}} = 10$  years

contrast, the tailing phenomenon occurred in the case of  $K_r=0.001$ , so that the slope of the concentration versus the pumping duration became small. Thus, the removal efficiency of the contaminants became smaller for cases in which the aquifer included a clay layer than for cases in which the homogeneous sand aquifer was without a clay layer. This change was probably because the transport of chemical compounds by advection and dispersion, which depended on the groundwater velocity, became small at the same time. The effects of advection and dispersion are smaller if the hydraulic conductivity is lower. In the cases of a hydraulic conductivity ratio  $K_r$  of less than 0.001, the tailing phenomenon occurred so that the removal efficiency of the contaminants was small. The concentration profiles were almost the same regardless of the different hydraulic conductivities. This was because the transport of chemical compounds by advection and dispersion disappeared so that only the transport of chemical compounds by diffusion, which did not depend on the groundwater velocity, was generated in the cases of a much lower hydraulic conductivity of the clay layer, namely,  $K_r=0.0001$  and  $K_r=0.00001$ . Figure 9 shows the concentration and the pore velocity levels in the remedia-

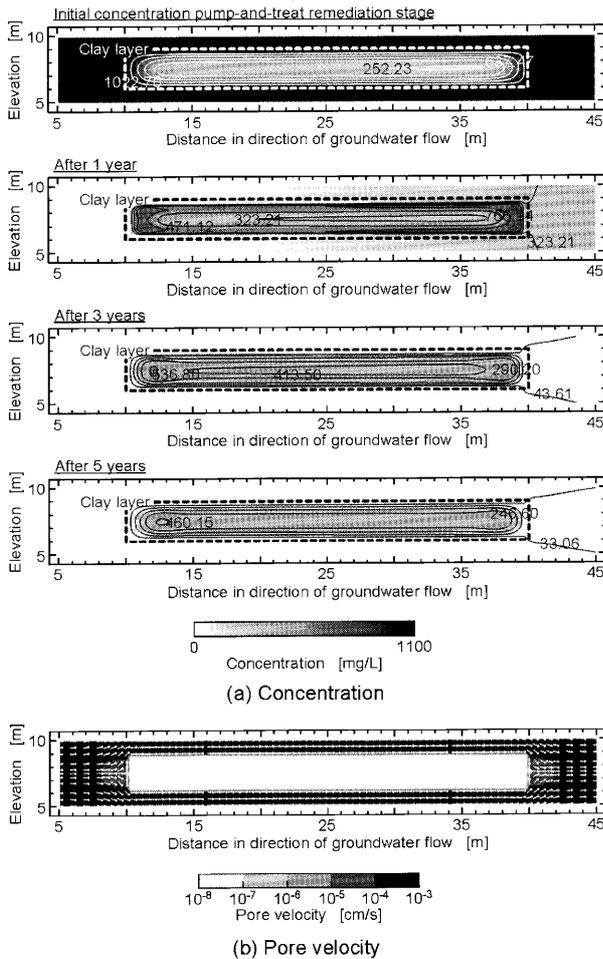


Fig. 11. Concentration and pore velocity in the remediation stage (case  $K_r=0.00010$ ):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.0001$ ,  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$  and  $T_{\text{cont}} = 10 \text{ years}$

tion stage if the contaminated site was a homogeneous sand aquifer (case with no clay layer). Figures 10 and 11 show the concentration and the pore velocity levels in the remediation stage for an aquifer which included a clay layer with a hydraulic conductivity of  $k_{\text{clay}} = 5.0 \times 10^{-5} \text{ cm/s}$  ( $K_r = 0.01$ ) and  $k_{\text{clay}} = 5.0 \times 10^{-7} \text{ cm/s}$  ( $K_r = 0.0001$ ), respectively. The contaminants in the sand aquifer were able to be flushed easily by a high groundwater velocity of  $|v_i| = 1.0 \times 10^{-4} \sim 1.0 \times 10^{-3} \text{ cm/s}$ , as shown in Fig. 9, if the aquifer was in a highly permeable homogeneous sand. As shown in Figs. 10 and 11, however, the contaminants in the aquifer which included a low permeable clay layer could not be flushed in a short period of time. This was because the contaminants were continuously provided into the aquifer around the clay layer by diffusion from the low permeable clay layer which remained contaminated, even when the contaminants in the highly permeable aquifer around the clay layer were flushed by pumping. In the case of  $K_r=0.01$ , the contaminants in the clay layer were not flushed as fast as for the case with no clay layer by a groundwater velocity of  $|v_i| = 1.0 \times 10^{-6} \sim 1.0 \times 10^{-5} \text{ cm/s}$ . In contrast, the contaminants in a much lower permeable clay layer, in the case of  $K_r = 0.0001$ , were unable to be transported by advection and

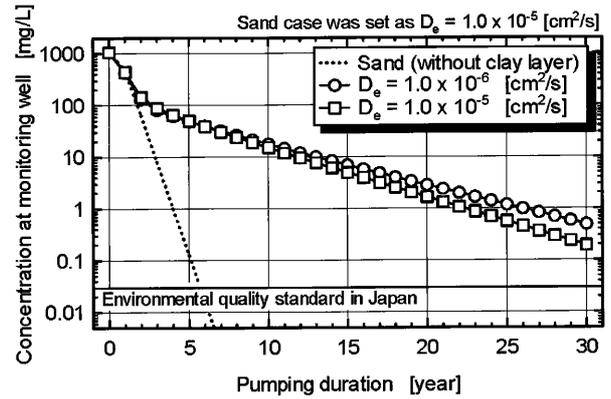


Fig. 12. Effects of the effective molecular diffusion coefficient on the concentration profiles at the monitoring well (D-series):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$  and  $T_{\text{cont}} = 10 \text{ years}$

dispersion because of the small groundwater velocity of  $|v_i| = 1.0 \times 10^{-8} \sim 1.0 \times 10^{-7} \text{ cm/s}$  in the clay layer. In addition, the initial concentration distribution during the remediation stage showed that the low permeable clay layer was not contaminated fully in the contamination duration of  $T_{\text{cont}} = 10 \text{ years}$ . Such heterogeneity in the concentration distribution may have a significant effect on the evaluation when determining the applicability of pump-and-treat remediation for contaminated sites. Clay layers are greatly sensitive to the removal efficiency of contaminants. In particular, the hydraulic conductivity of a clay layer has a significant effect not only on the remediation duration of the contaminated site, but also on the heterogeneity in the concentration distribution of the clay layer.

*Effects of the Effective Molecular Diffusion Coefficient*

The effects of the effective molecular diffusion coefficient on the contaminated groundwater concentration at the monitoring well are shown in Fig. 12. In this figure, the calculated concentration levels at the monitoring well were plotted after pump-and-treat remediation was used for the contaminated aquifer which included a clay layer whose size was  $H_{\text{clay}} = 3 \text{ m}$  and  $L_{\text{clay}} = 30 \text{ m}$ . The effective molecular diffusion coefficient was set at  $D_e = 1.0 \times 10^{-6} \text{ cm}^2/\text{s}$  and  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$ . The dash line shows the results for the case with no clay layer; there was only a sand aquifer in the analysis domain. In the case of no clay layer, effective molecular diffusion coefficient  $D_e$  was set at  $1.0 \times 10^{-5} \text{ cm}^2/\text{s}$ .

As shown in Fig. 12, the concentration profiles exhibited almost similar trends, even when the effective molecular diffusion coefficient was changed. The one order difference in the effective molecular diffusion coefficient did not have an effect on the predicted results for the groundwater concentration shortly after pump-and-treat remediation was started. However, the one order difference in the effective molecular diffusion coefficient may have a large effect on the predicted groundwater concentration for long-term predictions. Thus, the effective molecular diffusion coefficient may be an

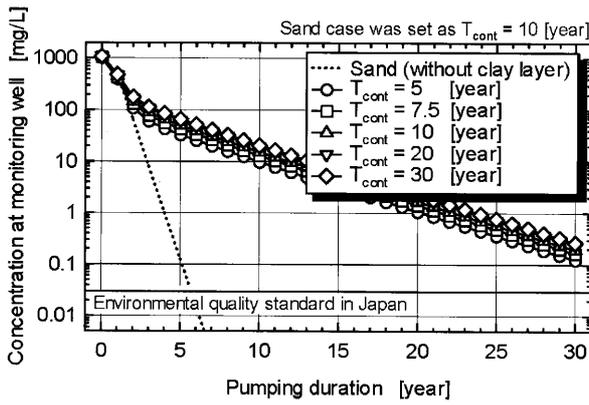


Fig. 13. Effects of the contamination duration on the concentration profiles at the monitoring well (T-series):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$  and  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$

important parameter in the case of an evaluation of a long-term remediation to decrease the groundwater concentration to a low concentration level for an aquifer which includes a clay layer.

*Effects of the Contamination Duration*

The effects of the contamination duration on the contaminated groundwater concentration at the monitoring well are shown in Fig. 13. In this figure, the calculated concentration levels at the monitoring well are plotted after pump-and-treat remediation was used for a contaminated aquifer including a clay layer. These results were computed by setting contamination duration  $T_{\text{cont}}$  at 5 to 30 years. The dash line shows the results for a case with no clay layer; there was only a sand aquifer in the analysis domain. In the case of no clay layer, contamination duration  $T_{\text{cont}}$  was set at 10 years.

As shown in Fig. 13, the concentration profiles exhibited almost similar trends, even if the contamination duration was changed. In the case of the homogeneous sand aquifer (case with no clay layer), the remediation duration for the contaminated site was approximately 6 years; this remediation duration was shorter than contamination duration  $T_{\text{cont}} = 10$  years, because the groundwater velocity was enhanced by pumping. In contrast, if the contaminated site was a heterogeneous aquifer with a clay layer, the tailing phenomenon occurred so that the remediation duration was significantly longer than the contamination duration. The concentration profiles and the remediation durations were almost the same in all cases except for the case with no clay layer. Figures 14 and 15 show the concentration around the clay layer in the remediation stage for contamination durations of  $T_{\text{cont}} = 5$  years and  $T_{\text{cont}} = 30$  years, respectively. The pore velocity levels are the same as those in Fig. 7, because physical and geometric parameters used in both analyses are the same and the flow velocity is calculated under the steady-flow condition. From the initial concentration distributions in the remediation stage, shown in Figs. 14 and 15, the clay layer was fully contaminated at a maximum concentra-

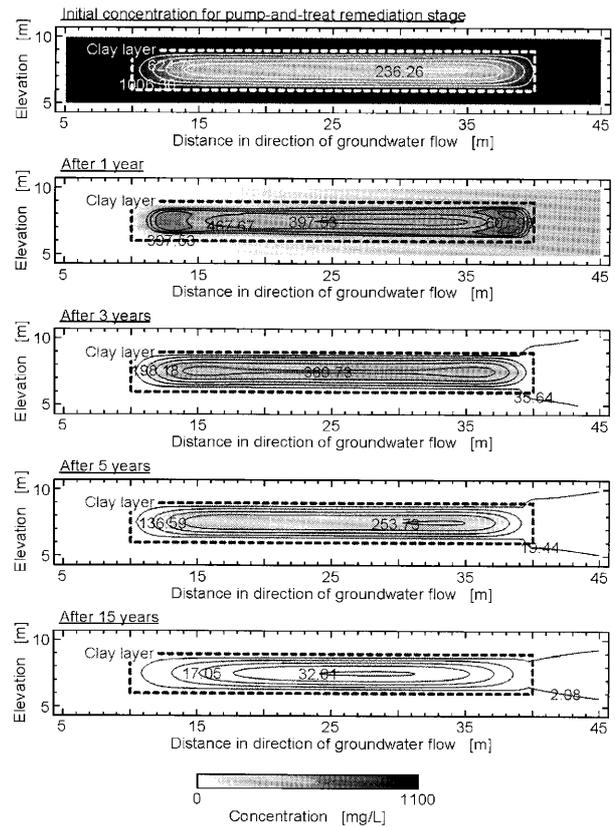


Fig. 14. Concentration in the remediation stage (case T-5):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$ ,  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$  and  $T_{\text{cont}} = 5$  years

tion of 1100 mg/L, if the contamination duration was very long ( $T_{\text{cont}} = 30$  years). In contrast, if the contamination duration was short ( $T_{\text{cont}} = 5$  years), the clay layer was contaminated heterogeneously, i.e., the interface between the sand aquifer and the clay layer was contaminated at the high concentration of 1100 mg/L and the center of the clay layer was contaminated at the low concentration of 236.26 mg/L. If pump-and-treat remediation was used for a contaminated site, including such a heterogeneous contaminated clay layer, it was difficult to remove the contaminants from the clay layer. This is because contaminants on the interface between the sand aquifer and the clay layer diffused not only to the sand aquifer, which was flushed by a fresh groundwater flow, but also to the center of the clay layer which remained at a low concentration. Some of the contaminants on the interface between the sand aquifer and the clay layer were transported into the clay layer regardless of the remediation term. As shown in Fig. 15, if the contamination duration was long ( $T_{\text{cont}} = 30$  years), the groundwater concentration in the center of the clay layer was decreased gradually from the initial groundwater concentration of  $c = 1065.32 \text{ mg/L}$  in the remediation stage. The groundwater concentration changed to 1051.50 mg/L after 1 year, 817.79 mg/L after 3 years, 546.60 mg/L after 5 years, and 68.69 mg/L after 15 years. If the contamination duration was short ( $T_{\text{cont}} = 5$  years), on the other hand, the groundwater concentration

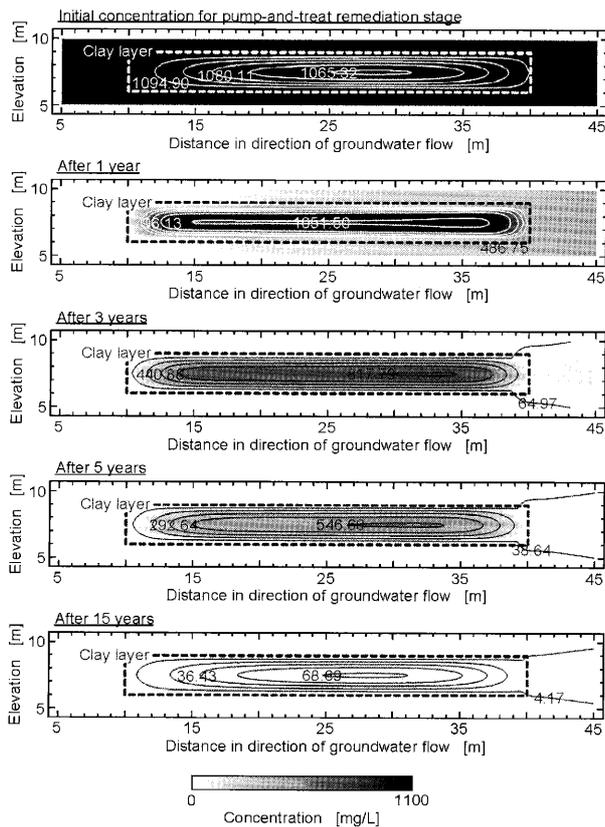


Fig. 15. Concentration in the remediation stage (case T-30):  $H_{\text{clay}} = 3 \text{ m}$ ,  $L_{\text{clay}} = 30 \text{ m}$ ,  $K_r = 0.001$ ,  $D_e = 1.0 \times 10^{-5} \text{ cm}^2/\text{s}$  and  $T_{\text{cont}} = 30 \text{ years}$

in the center of the clay layer was increased from the initial groundwater concentration of  $c = 236.26 \text{ mg/L}$  to  $c = 397.53 \text{ mg/L}$  after 1 year regardless of the remediation term, as shown in Fig. 14. Following this, the groundwater concentration in the center of the clay layer was not decreased easily; the groundwater concentration changed to  $360.73 \text{ mg/L}$  after 3 years,  $257.73 \text{ mg/L}$  after 5 years, and  $32.01 \text{ mg/L}$  after 15 years. Thus, it was obvious that the heterogeneity in the concentration distribution had an effect on the removal efficiency of the contaminants in the clay layer.

Since it is difficult for contaminants to infiltrate into a clay layer, the concentration distribution in the clay layer easily becomes heterogeneous, particularly under either of the following two conditions: (1) the hydraulic conductivity of the clay layer is low or (2) the thickness of the clay layer is large. In addition to these conditions, if the contamination duration is short, the concentration distribution will become more heterogeneous such that it becomes more difficult to remove the contaminants in the clay layer. Thus, the remediation duration does not agree simply with the contamination duration in cases where the contaminated site was an aquifer which included a large clay layer. Even if a contaminated site is discovered early, the remediation duration for the site may be long due to the distribution of the heterogeneous concentration in the clay layer. The contamination duration, which has an effect on the distribution of the heterogeneous

concentration in the clay layer, is consequently an important parameter. If the distribution of the heterogeneous concentration at a real contaminated site is assumed to be homogeneous, the performance of pump-and-treat remediation may be evaluated excessively, particularly in cases where the contaminated site includes a large clay layer.

## DISCUSSION

### Half-Life and the Remediation Duration

The analysis results are summarized in Table 3. The half-life was defined as the time required for the concentration of contaminated groundwater at the monitoring well to be cut in half. The half-life was calculated as follows:

$$T_{1/2} = \frac{\log 2}{k} \quad (4)$$

where  $T_{1/2} [T]$  is the half-life and  $k [1/T]$  is the slope of the logarithmic concentration versus the pumping duration. Equation (4) was given by fitting the changes in the concentration of the contaminated groundwater with the time at the monitoring well to the processes which were proceeded by the chemical first-order reactions,  $c = c_0 \exp(-kt)$ . The half-life was the inverse for slope  $k$  of the logarithmic concentration versus the pumping duration. The half-life was short if slope  $k$  of the logarithmic concentration versus the pumping duration was large, that is, if the removal efficiency was large. This slope  $k$  changed with time. If the contaminated site was an aquifer which included a clay layer, the removal efficiency in the cases of the aquifer with a clay layer was almost the same as in the case of a homogeneous sand aquifer within several months after pump-and-treat remediation was started. However, it became smaller after the tailing phenomenon occurred. Primary half-life  $T_{1/2, \text{primary}}$  was calculated from slope  $k_{\text{primary}}$  of the logarithmic concentration versus the pumping duration before the tailing phenomenon occurred. On the other hand, secondary half-life  $T_{1/2, \text{secondary}}$  was calculated from slope  $k_{\text{secondary}}$  of the logarithmic concentration versus the pumping duration after the tailing phenomenon occurred. The performance decrease index,  $I_p$ , was defined as the value into which secondary half-life  $T_{1/2, \text{secondary}}$  was divided by primary half-life  $T_{1/2, \text{primary}}$ . The performance decrease index indicates how much the removal performance of the contaminants decreased due to the tailing phenomenon. The remediation duration,  $T_{\text{target}}$ , was defined as the time required for the concentration of contaminated groundwater at the monitoring well to be decreased to the remediation target concentration. Note that remediation duration  $T_{\text{target}}$ , as shown in Table 4, was given by assuming the maximum concentration to be  $1100 \text{ mg/L}$  at the contaminated site and by assuming the remediation target concentration to be  $0.03 \text{ mg/L}$ .

As shown in Table 4, primary half-life  $T_{1/2, \text{primary}}$  was less than 0.5 years in almost all the cases. The concentration of contaminated groundwater at the monitoring well

**Table 3. Half-life and the remediation duration**

Case	Primary half-life $T_{1/2,primary}$ [year]	Secondary half-life $T_{1/2,secondary}$ [year]	Performance decrease index $I_p = T_{1/2,secondary} / T_{1/2,primary}$	Remediation duration† $T_{target}$ [year]
Effects of clay layer geometries				
H-1, L-10	0.353	0.357	1.009	6.00
H-1, L-30	0.364	0.371	1.020	6.17
H-3, L-10	0.492	2.154	4.376	27.83
H-3, L-30	0.472	3.235	6.848	38.67
Effects of clay layer hydraulic conductivity				
K <sub>r</sub> -0.00001	0.417	13.666	32.805	150.78
K <sub>r</sub> -0.00010	0.425	9.559	22.492	114.39
K <sub>r</sub> -0.00100	0.472	3.235	6.848	38.67
K <sub>r</sub> -0.01000	0.455	0.565	1.240	8.62
K <sub>r</sub> -0.10000	0.345	0.345	1.000	5.85
K <sub>r</sub> -1.00000 (non-clay)	0.334	0.334	1.000	5.70
Effects of effective molecular diffusion coefficient				
D-1.00E-06	0.456	3.988	8.742	46.13
D-1.00E-05	0.472	3.235	6.848	38.67
Effects of contamination time				
T-5	0.430	3.238	7.534	36.58
T-7.5	0.455	3.238	7.113	37.91
T-10	0.472	3.235	6.848	38.67
T-20	0.501	3.232	6.451	39.83
T-30	0.508	3.231	6.364	40.09

†assumed  $c_{initial} = 1100$  mg/L and  $c_{target} = 0.03$  mg/L.

**Table 4. Effects of the hydraulic gradient (pumping rate) in the remediation stage on the half-life**

Case	Primary half-life $T_{1/2,primary}$ [year]	Secondary half-life $T_{1/2,secondary}$ [year]	Performance decrease index $I_p = T_{1/2,secondary} / T_{1/2,primary}$
K <sub>r</sub> -0.00010	$i_{pump} = 1/250$	9.843	11.094
	$i_{pump} = 1/125$	0.425	22.492
K <sub>r</sub> -0.00100	$i_{pump} = 1/250$	4.760	5.315
	$i_{pump} = 1/125$	0.472	6.848
K <sub>r</sub> -0.01000	$i_{pump} = 1/250$	1.034	1.171
	$i_{pump} = 1/125$	0.455	1.240

was able to be decreased to half by pumping for half a year. It was concluded that pump-and-treat remediation was very effective if the initial concentration of groundwater was large at the contaminated site. The tailing phenomenon occurred under certain conditions, however, so that secondary half-life  $T_{1/2,secondary}$  grew long. In particular, this effect appeared in the case where the hydraulic conductivity of the clay layer was low. In the case of K<sub>r</sub>-0.00001, the hydraulic conductivity of the clay layer was  $5.0 \times 10^{-8}$  cm/s and secondary half-life  $T_{1/2,secondary}$  was increased significantly to 13.666 years.

If changes in the concentration of contaminated groundwater with time at the monitoring well were fitted to the processes which were preceded by the chemical first-order reactions, remediation duration  $T_{target}$  was calculated approximately as follows:

$$T_{target} = \frac{\log(c_{initial}/c_*)}{k_{primary}} + \frac{\log(c_*/c_{target})}{k_{secondary}}$$

$$\begin{aligned}
 &= \frac{\log(c_{initial}/c_{target}) + \log(c_{target}/c_*)}{k_{primary}} + \frac{\log(c_*/c_{target})}{k_{secondary}} \\
 &= \frac{T_{1/2,primary} - T_{1/2,secondary}}{\log 2} \log\left(\frac{c_{target}}{c_*}\right) \\
 &\quad - \frac{T_{1/2,primary}}{\log 2} \log\left(\frac{c_{target}}{c_{initial}}\right) \quad (5)
 \end{aligned}$$

where  $c_{initial}$  [M/L<sup>3</sup>] is the concentration at monitoring well before pump-and-treat remediation starts,  $c_{target}$  [M/L<sup>3</sup>] is the remediation target concentration,  $c_*$  [M/L<sup>3</sup>] is the concentration when the tailing phenomenon occurs. The term  $c_{target}/c_{initial}$  is the remediation target dimensionless concentration from the initial contaminated condition, and the term  $c_{target}/c_*$  is the remediation target dimensionless concentration from a contaminated condition after the tailing phenomenon occurs. Definitions of the above-mentioned parameters are summarized in Fig. 16.

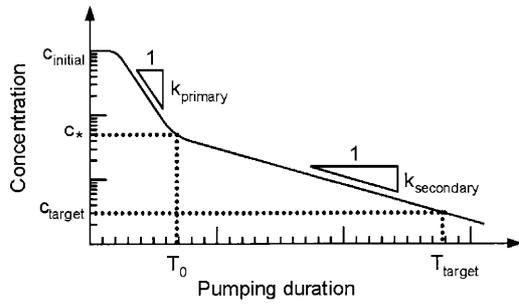


Fig. 16. Definition of the parameters

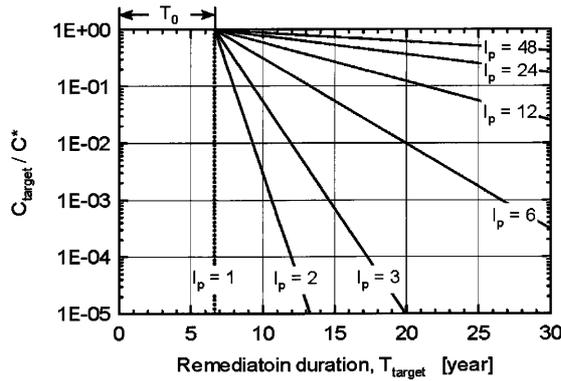


Fig. 17. Effects of the remediation duration and the performance decrease index on the concentration at the monitoring well:  $T_{1/2,primary} = 0.4$  year,  $T_{1/2,secondary} = T_{1/2,primary} \times I_p$

Figure 17 shows remediation duration  $T_{target}$  versus  $C_{target}/c_*$ . Primary half-life  $T_{1/2,primary}$  was set as 0.4 years, and secondary half-life  $T_{1/2,secondary}$  (performance index  $I_p$ ) was changed to the parametric. Remediation target dimensionless concentration  $C_{target}/C_{initial}$  was set as 0.00001. Symbol  $T_0$ , which was defined as the second term in Eq. (5), indicated one of two meanings, namely, (1)  $T_0$  was the remediation duration for a homogeneous sand aquifer, which was given from Eq. (5) under  $T_{1/2,primary} = T_{1/2,secondary}$  or (2)  $T_0$  was the tailing phenomenon at the starting time, which was given from Eq. (5) under  $C_{target} = c_*$ . The dash line shows remediation duration  $T_0$  for the homogeneous sand aquifer as  $I_p = 1$ . In the cases of an aquifer which includes a clay layer as  $I_p > 1$ , however, the tailing phenomenon occurred so that remediation duration  $T_{target}$  for the aquifer including a clay layer was longer than remediation duration  $T_0$  for a homogeneous sand aquifer. Remediation duration  $T_{target}$  for the aquifer with a clay layer was dependent on remediation target concentration  $C_{target}$ . If pump-and-treat remediation is stopped at the same time that the tailing phenomenon occurs, remediation duration  $T_{target}$  will be equal to  $T_0$ , because  $C_{target} = c_*$ . If the groundwater concentration is further decreased by continuous pumping in the tailing phenomenon, however, remediation duration  $T_{target}$  needs the extra pumping duration in addition to  $T_0$ . As shown in Fig. 17, the extra pumping duration was ineffective for the aquifer which includes a clay layer such as  $I_p > 6$ ; the thickness of the clay layer was larger than

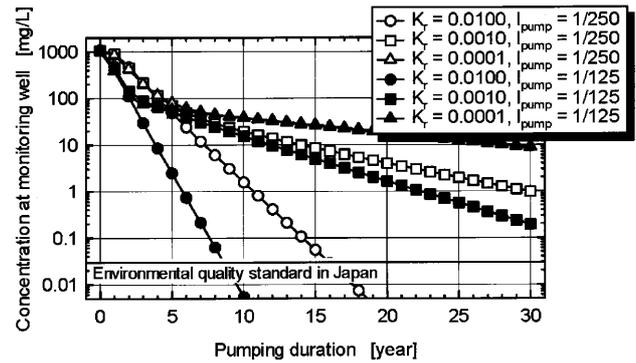


Fig. 18. Effects of the hydraulic gradient (pumping rate) in the remediation stage on the concentration profiles at the monitoring well:  $H_{clay} = 3$  m,  $L_{clay} = 30$  m,  $K_r = 0.001$ ,  $D_e = 1.0 \times 10^{-5}$  cm<sup>2</sup>/s and  $T_{cont} = 10$  years

3 m and the hydraulic conductivity of the clay layer was lower than  $5.0 \times 10^{-6}$  cm/s. This was because the groundwater concentration could not be decreased even 1-order from the tailing phenomenon starting concentration of  $c_*$ , even if pump-and-treat remediation was used continuously for 3 years after the tailing phenomenon occurred. It is possible to approximately evaluate the effects of the clay layer on the remediation duration from Fig. 17.

*Effects of the Pumping Rate on the Remediation Duration*

As shown in Fig. 17, pump-and-treat remediation was ineffective for the aquifer which included a clay layer such as  $I_p > 6$ ; the thickness of the clay layer was larger than 3 m and the hydraulic conductivity of the clay layer was lower than  $5.0 \times 10^{-6}$  cm/s. Hence, it was investigated whether or not the remediation duration could be shortened by increasing the pumping rate. This was evaluated by computing each analysis condition under the following two hydraulic gradients in the remediation stage, namely,  $i_{pump} = 1/250$  (small pumping rate) and  $i_{pump} = 1/125$  (large pumping rate). The analysis conditions were the same as  $K_r = 0.01000$ ,  $K_r = 0.00100$ , and  $K_r = 0.00010$ , shown in Table 2, except for hydraulic gradient  $i_{pump}$  in the remediation stage. The performance decrease indexes for these cases were  $I_p = 1.240$ ,  $I_p = 6.848$ , and  $I_p = 22.492$ , respectively, as shown in Table 3. The clay layer in both cases,  $K_r = 0.00100$  and  $K_r = 0.00010$ , had a significant effect on the remediation duration.

Figure 18 shows the effects of the hydraulic gradient (pumping rate) in the remediation stage on the concentration profiles at the monitoring well. The open plots are the calculation results for  $i_{pump} = 1/250$  (small pumping rate) and the closed plots are the calculation results for  $i_{pump} = 1/125$  (large pumping rate). In the case of  $K_r = 0.01000$ , the remediation duration was shortened by increasing the pumping rate. However, it became more difficult to shorten the remediation duration if the hydraulic conductivity of the clay layer became lower, such as  $K_r = 0.00100$  and  $K_r = 0.00010$ . Table 4 shows the effects of the hydraulic gradient (pumping rate) in the

remediation stage on the half-lives. These half-lives were calculated from Fig. 18. Primary half-life  $T_{1/2, \text{primary}}$  was cut in half by increasing the pumping rate from  $i_{\text{pump}} = 1/250$  to  $i_{\text{pump}} = 1/125$ . Primary half-life  $T_{1/2, \text{primary}}$  depended on the hydraulic gradient generated in the aquifer, so that primary half-life  $T_{1/2, \text{primary}}$  for the aquifer with a clay layer was almost the same as that for the homogeneous sand aquifer. In contrast, secondary half-life  $T_{1/2, \text{secondary}}$  was not shortened in the cases of a much lower hydraulic conductivity of a clay layer such as  $K_r = 0.00010$ , even if the pumping rate was doubled. This indicates that secondary half-life  $T_{1/2, \text{secondary}}$  is significantly related to the effects of the clay layer on remediation duration  $T_{\text{target}}$ . In general, secondary half-life  $T_{1/2, \text{secondary}}$  was much longer than primary half-life  $T_{1/2, \text{primary}}$ . Thus, secondary half-life  $T_{1/2, \text{secondary}}$  was important for evaluating the applicability of pump-and-treat to contaminated sites.

#### *Applicability of Pump-and-Treat System to Contaminated Sites*

In evaluating the applicability of the pump-and-treat system to contaminated sites, the characteristic of the concentration profile in the tailing phenomenon was important. It was shown as secondary half-life  $T_{1/2, \text{secondary}}$  in this paper. Secondary half-life  $T_{1/2, \text{secondary}}$  was significantly dependent on the hydraulic conductivity of the clay layer,  $k_{\text{clay}}$ , and the thickness of the clay layer,  $H_{\text{clay}}$ . The applicability of pump-and-treat remediation was large if at least one of the following two conditions was satisfied: (1) the hydraulic conductivity of the clay layer was greater than  $5.0 \times 10^{-5}$  cm/s or (2) the thickness of the clay layer was less than 3 m. In these cases, secondary half-life  $T_{1/2, \text{secondary}}$  was short, less than 3.5 years, so that the remediation duration which was required to decrease the contaminants to the remediation target was short, and it was able to be shortened by increasing the pumping rate.

The clay layer at the contaminated site had a significant effect on the applicability of pump-and-treat remediation. The effects of the clay layer were seriously dependent on the hydraulic conductivity of the clay layer and the thickness of the clay layer. It was unrealistic to investigate the physical parameters and the geometry conditions of all the clay layers at a real contaminated site. Considering such heterogeneity of an aquifer at a real contaminated site, therefore, it was concluded that it would be important to monitor the concentration of groundwater and to properly re-evaluate the applicability according to the newest concentration profiles.

It was difficult to evaluate the applicability of pump-and-treat remediation before this technology was used at a contaminated site. It was important to properly evaluate the applicability from the present monitored concentration profile.

## CONCLUSIONS

To evaluate the effects of a clay layer on the performance of pump-and-treat remediation, an advection-

dispersion analysis assuming non-sorption was calculated by changing five parametric variables, namely, the length of the clay layer, the thickness of the clay layer, the hydraulic conductivity of the clay layer, the effective molecular diffusion coefficient of the contaminants, and the contamination duration. The main results are shown below.

- (1) The amount of contaminants removed was significantly dependent on the thickness of the clay layer and the hydraulic conductivity of the clay layer. The difference in the thickness of the clay layer appeared significantly in the removal efficiency of the contaminants by the pump-and-treat remediation. On the other hand, the remediation duration was greatly increased if the hydraulic conductivity of the clay layer was less than  $5.0 \times 10^{-5}$  cm/s.
- (2) The contamination conditions of the clay layer when the pump-and-treat remediation was started were important. The remediation duration was evaluated as being short if the contamination conditions of the clay layer were assumed to be uniform in an averaged concentration when evaluating the performance of the pump-and-treat remediation. It is necessary to note that some contaminated sites may not be remedied in a short period of time, even if they are discovered early.
- (3) The pump-and-treat remediation was found to be effective if at least one of the following two conditions was satisfied, namely, the hydraulic conductivity of the clay layer was greater than  $5.0 \times 10^{-5}$  cm/s or the thickness of the clay layer was less than 3 m. In such cases, the remediation duration was short, and it could be shortened by increasing the pumping rate. In contrast, if at least one of the above-mentioned conditions was not satisfied, the amount of contaminants removed per time was decreased seriously; a pumping duration of 6 years or more was required to decrease the concentration of contaminated groundwater at the monitoring well to half.

The above-mentioned conclusions are obtained by the advection-dispersion analysis without considering the sorption phenomenon in order to clearly present the physical effects (the hydraulic conductivity, the scale, and the geometric condition) of the heterogeneous ground condition, the clay layer, which was included in the aquifer. Therefore, it is noted that the conclusions obtained in this study may be unable to be applied directly to the real sites in a quantitative aspect. In the remediation stage where the contaminants were flushed by the groundwater flow, the desorption phenomenon would occur possibly in a more complex manner than the adsorption phenomenon. The factors to complicate the desorption are, for example, (1) the effects of the concentration-dependent desorption mechanism, (2) the effects of the hysteresis in the relation between the adsorption and the desorption. Thus, it is difficult to use the advection-dispersion analysis shown in Eq. (2) for the prediction of the contaminants transport in the remedia-

tion stage, because Eq. (2) neglects the concentration-dependency and the hysteresis of the desorption reaction. In order to predict the transport of the contaminants in the remediation stage more correctly, the effects of concentration-dependency and hysteresis on the desorption must be investigated experimentally, and the mathematical transport model with consideration of the desorption must be developed.

The applicability of pump-and-treat remediation to contaminated sites is significantly dependent on the physical and the geometric conditions of the clay layer. Thus, it is important to clarify the geometric condition, the scale, and the position of the clay layers which are included in a real site. However, it is very difficult to obtain the characteristics of the conditions in detail for clay layers at the unknown positions because a long duration and high costs are required for the investigation. On the other hand, the clay layer in the aquifer affects significantly the profiles of the groundwater concentration at a monitoring well. Therefore, knowledge with respect to the characteristics of the concentration profile at the monitoring well may be able to provide the information on the clay layer which is not found by the investigation. It is concluded that monitoring the contaminant concentration in groundwater is important also for the understanding of the aquifer-structure; the geometric condition, the scale and the position of the clay layer which is included in the site. It is possible to judge reasonably whether to continue the pump-and-treat remediation technology or to change to a different remediation technology, if the concentration profile obtained by monitoring at a real site is compared with the analysis results investigating effects of physical and geometric conditions on the concentration profile as like the analysis results reported in this paper.

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