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Modeling of Remediation Design in Theoretically Heterogeneous Domain

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Abstract

Probabilistic approaches are applied to the problem of groundwater remediation design to consider the risk of design and heterogeneity of real condition. Hydraulic conductivity fields are generated by two methods. First, the homogeneous domains which have the hydraulic conductivity with log-normal distribution are constructed by using Latin Hypercube method. Second, random fields with a certain spatial correlation are also generated. The optimal solutions represented by cumulative distribution function (CDF) of relative cost are calculated by three different manners. The one uses the homogeneous domains with the optimal design of base condition. It shows that very wide range of cost and the influences of different penalty values. The other one uses the random field with same design and shows narrow range of cost. These CDF can reflect on the risk of optimal solution in a simple example condition and be effective in estimating the cost of groundwater remediation.

Key word : remediation design, optimization, heterogeneity

1. Introduction

For many practical problems of groundwater hydrology such as aquifer development, assessment of contamination, or contaminated aquifer remediation, the uncertainties caused by heterogeneity of hydrogeological parameters raise a question of application to deterministic values commonly used. Geostatistical method has been used so as to solve this problem and shows a solution with probabilistic value or a certain distribution instead of only a deterministic value (McLaughlin and Townley, 1996; Zimmerman et al., 1998).

In this study, the cumulative distribution functions for relative cost are constructed and compared using two cases. Homogeneous domains with a log-normal distribution and heterogeneous domains with specific spatial correlation for hydraulic conductivity are assumed in the condition of optimal design for base condition.

2. Method of setting up domains for numerical experiments

2.1 Latin Hypercube

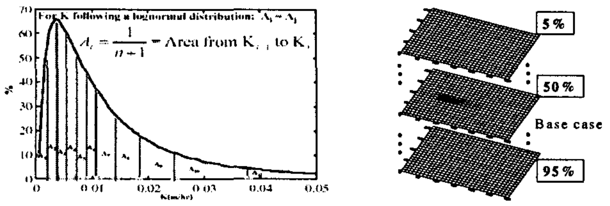

Figure 1. Illustration of concept of equal-area sampling using a log-normal distribution of the hydraulic-conductivity field (Pinder et al., 2001)

Homogeneous domains are derived from Latin hypercube method. In this approach, the probability density function that describes the uncertainty in hydraulic conductivity is separated into equal areas. When equal-area sampling is used to determine the samples that are used to represent the uncertainty in the hydraulic conductivity, each of the domains analyzed in the optimization process has an equal probability of occurrence. This simplifies the optimization process because the weight associated with each scenario is equal. In this homogeneous case, hydraulic conductivities of all domains are on the log-normal distribution where the mean is 1.0×10^{-4} m/s and more than 99% of them is included from 1.0×10^{-3} to 1.0×10^{-3} m/s.

2.2 Simulated Annealing

Simulated annealing method is applied in order to make the spatial correlated domains. This method can generate equiprobable realizations without the need to depend on any distributional assumptions about the parent random function that makes a value of whole domain and offers the possibility of handling multiple constraints (Olea, 1999). The log-normal distribution assumed in this experiment is equal to the case of homogeneous domains; the mean is 1.0×10^{-4} m/s and more than 99% of them is included from 1.0×10^{-3} to 1.0×10^{-5} m/s.

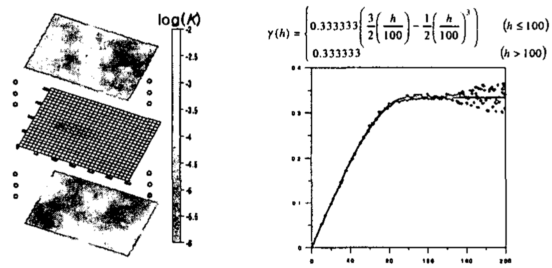

Figure 2. Generated domains and their experimental variogram

3. Experimental

3.1 Base Condition

A new domain is assumed. It is an isotropic, homogeneous, and unconfined aquifer. It is discretized into 40 by 31 finite difference blocks. No-flow boundaries are assigned to the upper and lower in the horizontal section, and the top and bottom in the vertical section of the aquifer. The expected pumping well can be located around the domain. Other information for aquifer and contaminant is in Table 1. It is supposed that this domain is the base condition for following cases with homogeneity under a certain probabilistic distribution and with heterogeneity under a certain spatial correlation.

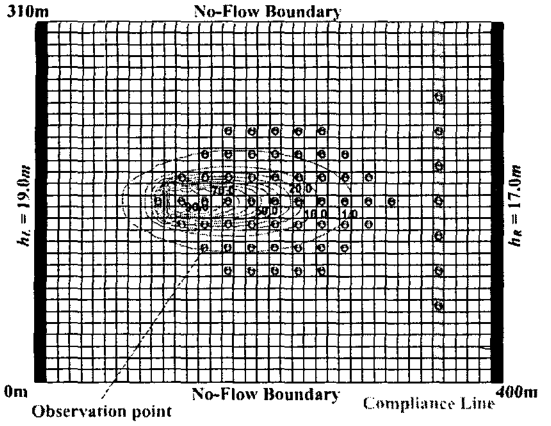

Figure 3. Domain of base condition

Table 1. parameters for aquifer and contaminant of base condition

Parameter	Value
Hydraulic conductivity, K(m/day)	8.64
Porosity, θ	0.25
Aquifer thickness, b(m)	20
Longitudinal dispersivity, α_L(m)	6.855
Transverse dispersivity, α_T(m)	1.371
Medium bulk density, ρ_b(kg/m^3)	1700
Distribution coefficient for linear sorption, K_d(L/mg)	1.58×10^{-7}

3.2 Objective Function

The objective function is given by:

$$\text{Minimization}\quad A_1\sum_{j=1}^{m}\left\{\sum_{i=1}^{n}Q_{i,j}(q_{i,j},t_{i,j})\right\}+A_2\sum_{i=1}^{n}Min\left(\sum_{j=1}^{m}q_{i,j},1\right)$$
$$+\omega_1(C^{\max},C^*,t^{\max},t^*,s^{\max},s^*)\times P_1+\omega_2(C_k^{\max},C_k^*)\times P_2 \quad (1)$$

subject to

$$C_{k,j}<C^* \qquad k=1,\cdots,K \quad j=1,\cdots,T \quad (2)$$
$$s_{i,j}<s^{\max} \qquad i=1,\cdots,N \quad j=1,\cdots,T \quad (3)$$
$$q_{i,j}^{\min}<q_{i,j}<q_{i,j}^{\max} \qquad i=1,\cdots,N \quad j=1,\cdots,T \quad (4)$$

where $A1$ is the cost of unit pumping volume; $A2$ is the cost of one well installation; $P1$ is the penalty cost for violation of concentration constraint within the compliance line; $P2$ is the penalty cost for outflow of contaminant plume that has more concentration than the concentration constraint; $C_{out}^{\max}$ is the maximum concentration of outflow through the compliance line; ω_1 and ω_2 are the weighting values for P1 and P2, respectively; C^* is 1.0 mg/L. Table 2 shows the optimal design for the base condition.

Table 2. Optimal design for base condition

Pumping well	Location(m)		Pumping rate (㎥/day)
	X	Y	
PW-1	165	155	60.96
PW-2	205	155	268.17
Total pumping rate			329.13
Time	1006.3 days		
Total pumpingvolume	331000㎥		
Realtive cost	531200		

3.3 Result for the Case using Latin Hypercube

The relative cost of base condition has 0.26 of cumulative probability. It means that only 26% of all domains are remedied by the base optimal design, and that the probability of success for remediation in this case is 26% if the optimal design of this relative cost is applied. Also, it means that other domains require additional treatment in order to decrease the contaminant concentration. The extremely high value of hydraulic conductivity on the tail of the log-normal distribution causes this outflow. The risk factor in this study is defined by:

$$Risk\ factor_i = (Cost_{i,base})\ /\ (Cost_{base}) \quad (1)$$

where $Risk\ factor_i$ is the risk factor for the i-th generated domain; $Cost_{base}$ is the relative cost of the base condition; $Cost_{i,base}$ is the relative cost of the i-th generated domain using the optimal design of the base condition.

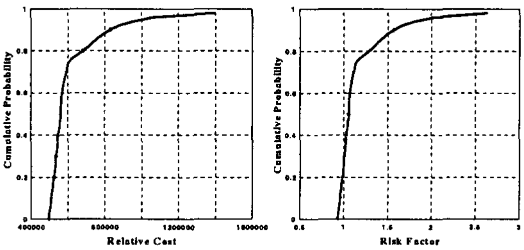

Figure 4. Relative cost and risk factor for homogeneous case

3.4 Result for the Case using Simulated Annealing

The range of the relative cost is narrower than that of the homogeneous case. The maximum cost is only about 1.5 times more than the minimum one. The probability of success is about 18%. In field condition, the extreme example of homogeneous case hardly exists when the sampling data is given. The hydraulic conductivity varies under a spatial correlation. So, This heterogeneous case is more adequate than the homogeneous case to evaluate cost-effective remediation design and the analysis of risk factor. The range of risk factor defined in above chapter is from 0.87 to 1.34 in respect to the relative cost. This result shows the small gap between the conventional method using the representative value of hydraulic conductivity and the stochastic method using the heterogeneous domains with spatial correlation. So, It means that this method using the base condition may be reasonable process for designing and analyzing the remediation strategy.

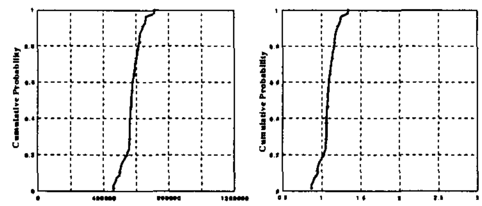

Figure 5. Relative cost and risk factor for heterogeneous case

4. Conclusion

The influences of spatial variation of hydraulic conductivity on the optimal remediation design are examined. Under the log-normal distribution, the homogeneous case using Latin hypercube method and the heterogeneous case using simulated annealing method is applied to the problem of minimizing total pumping volume with penalties. The conclusions for these cases follow. To analyze uncertainty and risk of failure, it is effective to design optimal remediation strategy using stochastic approach. Assumption of homogeneous domains with equal probability makes wide and unrealistic rage of cost and risk factor. They include some domains with extremely high hydraulic conductivity. These makes unrealistic feature, and the homogeneous case may be not adequate to evaluate the risk factor based on the cost. The heterogeneous case shows more realistic than the homogeneous case. Although the spatial correlated heterogeneous case is assumed, it has the limitation not to exist conditional points. If they are, the ranges of the cost and risk factor have more practical value.

Given from results, it shows that stochastic approaches are required and spatial correlation is important in order to design and evaluate the optimal remediation strategy. The simple homogeneous case using representative hydraulic conductivity may be improper to examine the cost-effective design and risk factor.

5. Acknowledgement

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