Simulation of landfill leachate polluting groundwater considering the liquid-solid coupling action

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Abstract: Deformation of porous media results in changes within the pores and fractures, and then affects the seepage process of the liquid within porous media; and inversely, liquid seepage induces seepage forces and affects the deformation of the porous media. So, the interaction of the porous media and the fluid is a coupled process. Obviously the coupled process can affect the transport and migration of contaminants in a porous media. In this paper coupled mathematical models have been presented to describe the full process of liquid seepage, solid deformation and contaminant transport and migration, and the models were adopted to simulate the process of landfill leachate polluting groundwater. The results clearly demonstrate that there are differences between the coupled and non-coupled processes and show that the effects of coupling cannot be ignored. This paper provides a significant theoretical basis for predicting the effect of landfill leachate on the environment.

Résumé: La déformation des médias poreux change les pores et les ruptures dans elle, et puis affecte le procédé d'infiltration du liquide dans des médias poreux; et inversement, l'infiltration du liquide induit la force d'infiltration et affecte la déformation des médias poreux. Ainsi, l'interaction des médias poreux et le fluide dans lui est des processus couplés. Les processus couplés évidemment peuvent affecter le transport et la migration des contaminants dans des médias poreux. En cet article, les modèles mathématiques couplés ont été développés pour décrire le plein processus de l'infiltration liquide, de la déformation et du transport plein et de la migration de contaminant, et les modèles ont été adaptés pour simuler le processus des eaux souterraines de pollution de leachate de remblai. Les résultats précisent que les différences de l'action d'accouplement et de l'action de désaccoupler sont évidentes et les effets de l'accouplement ne peuvent pas être ignorés. Cet article fournit les bases théoriques significatives pour prévoir l'effet du leachate de remblai sur l'environnement.

Keywords: environmental protection, landfill, leachate, permeability

INTRODUCTION

Municipal solid waste (MSW) has already become one of the main factors, which adversely influence the environment during the course of city construction and growth. The treatment of MSW has also become a "bottleneck problem", restricting the growth and development of urban areas. About 1/3 of the 670 large and medium cities in China are surrounded by solid waste sites, and leachate migrating from the waste mass migrates to the surface water and groundwater. The resultant contamination brings latent hazard, which cannot be ignored, to the cities. It has been estimated that in the period to 2006, the annual output of MSW will be about 180,000,000 tons. Currently, the waste disposal methods are primarily burial, incineration, electric power generation, composting and so on. Decreases in the volume and contaminating effects cannot be achieved due to the poor disposal techniques. MSW landfill is often adopted in waste disposal, because of its advantage in terms of low investment and simple technology. At the same time, these MSW landfill method may cause many environmental problems. Currently, many MSW landfills cannot meet environmental standards, for example, 368 of 386 MSW landfills in operation are not regulated in Peking, China, and of these 95% present a serious threat to the environment. Leachate from MSW landfill is a latent pollution source and the occurrence of leachate leakage, due to poor management can result in serious environmental contamination in the surrounding area. For example, in the Cao mountain landfill site of Anhui province in China, water quality determinations have identified high levels of contamination. Therefore, numerical simulation of the environmental pollution process from MSW landfill leachate is important to the evaluation of environmental risk associated with MSW landfills and also to the environmental pollution control process.

With the MSW problems being increasingly prominent, the occurrence of groundwater contamination is increasingly frequent; accordingly, the study of groundwater contamination resulting from MSW landfill leachate has become an increasingly focused issue. Many researchers have carried out experimental and theoretical studies on MSW landfill leachate and groundwater contamination, including the mechanisms driving leachate generation, its translation and transport process, pollution range, distribution characteristics and its fate in the environment. Examples include:

- an analysis of the groundwater contaminating processes resulting from the solid waste using 2D and 3D analytical solutions.

- A study of the contaminant migration and transport process in groundwater, which provided the theoretical basis for the prevention of groundwater contamination.
- A comparison of the transport velocity and characteristics of leachate migration through three different composite liners using 2-D and 3-D water quality models, which derived the retention characteristics of the different liners to different contaminants and provided the foundation for designed procedures to decrease the MSW impact on groundwater.
- A 1-D mathematical model of the leachate dispersion and transport components.
- A 2-D model to describe leachate seepage in porous media and dual-porosity media.
- Leaching experiments to simulate groundwater contamination by landfill leachate.

Predicting the pollution range of the landfill with the above models can provide a quantitative basis for prevention the landfill leachate from contaminating groundwater. However, the groundwater and contaminant transport and migration process in porous media is a coupled process of fluid flow seepage and porous media deformation. Deformation of the porous media has the potential to change the pores and fractures within it, thereby affecting the seepage processes of fluid flow in porous media; and inversely, seepage of fluid induces seepage force and affects the deformation of the porous media, so that the interaction of porous media and the fluid within it is coupled processes. Obviously, the coupled processes can affect the transport and migration of contaminants in the porous media. In this paper, coupled mathematical models have been developed to describe the full process of fluid flow seepage, solid deformation and contaminant transport and migration, and the models were adopted to simulate the real process of landfill leachate polluting groundwater. Based on the model, differences in the simulated landfill leachate seepage process with and without coupled action were compared.

GOVERNING EQUATIONS

The governing equations of the MSW landfill leachate transport and migration in groundwater include equations describing the liquid-solid coupling process and the solute movement. The liquid-solid coupling equations are a combination of equations of stress and seepage fields.

In this paper, theoretical formulation of the coupling mathematic model is based on the following assumptions:

1) The rock and soil material is an isotropic geological media and it belongs to porous elastic continuum;

2) The deformation of solid matrix abides by Terzaghis' law of effective stress, described as follows

$$\sigma_{ij} = \sigma'_{ij} + p\delta_{ij} \tag{1}$$

where σ_{ij} is the tensor of total stress, σ'_{ij} is the tensor of effective stress, p is pore pressure, and δ_{ij} denotes Kronecker sign.

3) Darcy's law is valid for fluid flow in rock and soil, that is

$$q_i = -\frac{k_i}{\mu\gamma} p_{,i} \tag{2}$$

where q_i is the velocity of fluid flow, k_i is the permeability of fluid flow, μ is dynamic viscosity, γ is bulk specific gravity of fluid flow and p is the density.

EQUATIONS OF THE STRESS FIELD

1) Equilibrium equation of stress (neglecting the body forces) is written as follows

$$\sigma_{ij,j} = 0 \tag{3}$$

2) Geometrical equation (the relation of stress and displacement) is described as the following

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \tag{4}$$

where ε_{jj} denotes the strain component, $u_{i,j}$, $u_{j,i}$ denotes the partial differentiation of the strain component to the coordinate.

3) Constitutive relation (the relation of strain and stress) can be described as:

$$\sigma'_{ij} = 2G(\frac{v}{1+v}\varepsilon_v + \varepsilon_i) \tag{5}$$

where $G = \dfrac{E}{2(1+v)}$ is the shear modulus of the porous medium, E is elastic modulus of rock and soil, v is Poisson's ratio, and $\varepsilon_v = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is volumetric strain.

4) Equilibrium equation of rock described with displacement

The equilibrium equation of rock described with displacement may be obtained by combining Eqs. (1), (3), (4) and (5).

$$\frac{G}{1-2v} u_{j,ji} + G u_{i,jj} + p_{,i} = 0 \qquad (6)$$

EQUATIONS OF THE SEEPAGE FIELD

It is assumed that the porosity of porous media is n and its saturation is s. Because the seepage process occurs in an elastic porous media, both the fluid and the solid have velocity, that is, the deformation of the porous media also has its velocity. So when considering the liquid-solid coupling process, the fluid flow velocity can be described as:

$$V_f = V_r + V_s \qquad (7)$$

where V_f, V_s denotes the absolute velocity of the fluid flow and the solid granules, respectively. V_r is the fluid flow relative velocity to the solid particle, and it can be written as:

$$V_r = \frac{1}{nS} q_f \qquad (8)$$

where q_f is Darcy's velocity, described as:

$$q_f = -\frac{K k_{rf}}{\mu} gradp \qquad (9)$$

where K is the absolute intrinsic permeability of fluid flow, k_{rf} denotes the relative intrinsic permeability of fluid flow.

Mass conservation equation of the porous media skeleton is described as:

$$div[\rho_s (1-n) V_s] + \frac{\partial[\rho_s (1-n)]}{\partial t} = 0 \qquad (10)$$

It is assumed that the porous media granules cannot be compressed, and the deformation of porous media is induced by the compression of pores. As a result, the saturation condition, $S=1$, so the mass conservation equation of the compressible fluid flow can be written as:

$$div[n \rho_f V_f] + \frac{\partial(n \rho_f)}{\partial t} = 0 \qquad (11)$$

Simplifying Eqs. (10) and (11) obtains:

$$\rho_s (1-n) divV_s + (1-n)\frac{\partial \rho_s}{\partial t} + \rho_s \frac{\partial(1-n)}{\partial t} = 0 \qquad (12)$$

$$\rho_f divV_f + n\rho_f divV_s + n\frac{\partial \rho_f}{\partial t} + \rho_f \frac{\partial n}{\partial t} = 0 \qquad (13)$$

Taking Eqs. (12) and (13), dividing the term on the left by ρ_s, ρ_f respectively, and then combining them, we obtain:

$$divV_f + divV_s + \frac{n}{\rho_f}\frac{\partial \rho_f}{\partial t} + (1-n)\frac{1}{\rho_s}\frac{\partial \rho_s}{\partial t} = 0 \qquad (14)$$

The state equation of the fluid flow under the condition of constant temperature can be written as:

$$\rho_f = \rho_0 e^{\beta_f (p-p_0)} \qquad (15)$$

where β_f is the compression coefficient, p is pore pressure, and p_0 is reference pressure.

By using Eq. (15), we can obtain:

$$grad\rho_f = \rho_f \beta_f gradp \bullet \frac{1}{\rho_f}\frac{\partial \rho_f}{\partial t} = \beta_f \frac{\partial p}{\partial t} \quad (16)$$

The modulus of compressibility of the porous media skeleton, K_s, is defined as:

$$\frac{1}{\rho_s}\frac{\partial \rho_s}{\partial t} = \frac{1}{K_s}\frac{\partial p}{\partial t} = \beta_s \frac{\partial p}{\partial t} \quad (17)$$

where β_s is coefficient of compressibility of the porous media skeleton, and $\beta_s = 1/K_s$.

Introducing Eqs. (9), (16) and (17) into Eq, (14), we can obtain:

$$div(-\frac{Kk_{rf}}{\mu} gradp) + divV_s + n\beta_f \frac{\partial p}{\partial t} + \beta_s(1-n)\frac{\partial p}{\partial t} = 0 \quad (18)$$

It is assumed

$$n\beta_f + (1-n)\beta_s = \beta \quad (19)$$

Combining Eqs.(18) and (19), the differential equation satisfying the pore pressure of porous media is obtained:

$$\frac{Kk_{rf}}{\mu}\nabla^2 p = divV_s + \beta \frac{\partial p}{\partial t} \quad (20)$$

GOVERNING EQUATIONS FOR THE LIQUID-SOLID COUPLING PROCESS

Because

$$V_s = \frac{\partial u}{\partial t}, \varepsilon_v = divu = \varepsilon_x + \varepsilon_y + \varepsilon_z, divV_s = \frac{\partial \varepsilon_v}{\partial t} \quad (21)$$

Eq. (20) may be rewritten as:

$$\frac{Kk_{rf}}{\mu}\nabla^2 p = \frac{\partial \varepsilon_v}{\partial t} + \beta \frac{\partial p}{\partial t} \quad (22)$$

Deriving the left hand side of Eq.(6) for x, y, z

$$(\frac{G}{1-2v} + G)\nabla^2 \varepsilon_v = \nabla^2 p \quad (23)$$

Integral transformation is adopted in the left and right hand side of Eq. (23) to obtain the following equation:

$$(\frac{G}{1-2v} + G)\varepsilon_v = p + f(x,y,z,t) \quad (24)$$

Introducing Eq. (24) into Eq. (23), we may obtain:

$$\frac{Kk_{rf}}{\mu}\nabla^2 p = (\alpha + \beta)\frac{\partial p}{\partial t} \quad (25)$$

where, $\alpha = 1/(\frac{G}{1-2v} + G)$.

MATHEMATICAL MODEL FOR THE LIQUID-SOLID COUPLING PROCESS

From the above analysis, the governing equation describing the coupled liquid-solid process in the groundwater seepage problem has been obtained, and initial and boundary conditions are needed to form the mathematical model describing the coupled liquid-solid process in the groundwater seepage problem.

The initial and boundary conditions are defined by the following:

① Initial condition: $p\big|_{t=0} = p_0$ (26)

② Dirichlet boundary condition: $p\big|_{\Gamma_1} = p_1$ (27)

③ Neumann boundary condition: $\frac{Kk_{rf}}{\mu}\frac{\partial p}{\partial n}\Big|_{\Gamma_2} = q$ (28)

With the above equations, the liquid-solid coupling mathematical model describing the groundwater seepage may be written as:

$$\begin{cases} \frac{Kk_{rf}}{\mu}\nabla^2 p = (\alpha+\beta)\frac{\partial p}{\partial t} \\ p\big|_{t=0} = p_0 \\ p\big|_{\Gamma_1} = p_1 \\ \frac{Kk_{rf}}{\mu}\frac{\partial p}{\partial n}\Big|_{\Gamma_2} = q \end{cases}$$

THE DYNAMIC EQUATION FOR THE CONTAMINANTS TRANSPORT AND MIGRATION IN ENVIRONMENTAL MEDIUM

Considering the processes of contaminant diffusion, absorption-desorption and biodegradation in environmental media, we can obtain the following 2-D non-equilibrium absorption dynamic governing equation:

$$\frac{\partial}{\partial t}(\theta C) + \rho\frac{\partial S}{\partial t} = \frac{\partial}{\partial x}\left[\theta\left(D_{xx}\frac{\partial C}{\partial x} + D_{xy}\frac{\partial C}{\partial y}\right)\right] + \frac{\partial}{\partial y}\left[\theta\left(D_{yx}\frac{\partial C}{\partial x} + D_{yy}\frac{\partial C}{\partial y}\right)\right] - \frac{\partial}{\partial x}(V_x C) + \frac{\partial}{\partial y}(V_y C) - \lambda\theta C \quad (29)$$

where C is the concentration of contaminants in groundwater, S is the absorption concentration of contaminants in the solid-liquid interface, θ is volumetric water content, V_x, V_y is the Darcy's velocity in x and y direction, respectively, ρ denotes the volume density, λ denotes coefficient of biodegradation rate, and D_{ij} is tensor of diffusion coefficient.

Absorption is one of the main factors that influence the transport and migration, fate, and bio-effects of contaminants in solid phase and water. Two main mechanisms occur with respect to the absorption of contaminants, distribution and surface absorption. In the solid-liquid environmental system, the absorption process is a dynamic reversible non-equilibrium process, the following governing equation can be adopted to describing the absorption behaviour of contaminants in solid-liquid surface:

$$\frac{\partial S}{\partial t} = k\theta(k_d C - S) \quad (30)$$

where k is the first order absorption-desorption rate constant, k_d is the distribution coefficient between porous media and water.

INITIAL AND BOUNDARY CONDITONS FOR THE CONTAMINANT CONCENTRATION FIELD

Initial condition:

$$C(x,z,t)\big|_{t=0} = C_0 \quad (31)$$

$$S(x,z,t)\big|_{t=0} = S_0 \quad (32)$$

Input boundary condition, that is, when $C(x,z,t) = C(0,0,t)$:

$$-\theta\left(D_{xx}\frac{\partial C}{\partial x} + D_{xy}\frac{\partial C}{\partial z}\right) - \theta\left(D_{yx}\frac{\partial C}{\partial x} + D_{yy}\frac{\partial C}{\partial z}\right) + \theta(V_x C + V_z C) = (V_x + V_z)C_0 \quad (33)$$

Output boundary condition, that is, when $C(x,z,t) = C(\infty,\infty,t)$

$$-\theta\left(D_{xx}\frac{\partial C}{\partial x} + D_{zz}\frac{\partial C}{\partial z}\right) - \theta\left(D_{yx}\frac{\partial C}{\partial x} + D_{zz}\frac{\partial C}{\partial z}\right) = 0 \quad (34)$$

where C_0, S_0 denote the initial concentration in liquid phase and solid-liquid interface.

From the above analysis, we conclude that the deformation of porous media influences the seepage of groundwater, with a resulting influence on the concentration distribution of contaminants in groundwater.

SIMULATION OF LANDFILL LEACHATE POLLUTING THE GROUNDWATER

Using the above liquid-solid coupling model and the contaminant transport and migration model, we can simulate the landfill leachate polluting the groundwater by finite element methods (FEM).

As an example, in this paper, a hypothetical landfill of 200×100m^2 and its zone of influence of 400×200m^2 has been analyzed. The rock stratum is divided three layers, including an aquifer in the middle and two impervious layers in the upper and below, respectively. An impermeable layer is surrounding the landfill.

The initial and boundary conditions are as follows:

On the left boundary: Displacement: $d_x = 0$, $d_y = free$; Pore pressure: $p = 50KPa$; Concentration: $C = 0$

On the right boundary: Displacement: $d_x = 0$, $d_y = free$; Pore pressure: $p = 10KPa$; Concentration: $C = 0$

On the bottom boundary: Displacement: $d_x = 0$, $d_y = 0$; water flux: $q = 0$; Concentration: $C = 0$

And at the bottom of the landfill: $C = 50 g / m^3$.

The only load at the site is gravity.

The main parameters for the hydrology, geology and mechanics of the rock are listed in table 1.

Table 1. Input parameters for model simulation

Rock stratum	Parameters	Value	Rock stratum	Parameters	Value
Upper layer	Young's modulus (MPa)	6.5	Lower layer	Young's modulus (MPa)	7.9
	Poisson's ratio	0.25		Poisson's ratio	0.25
	Permeability coefficient in x direction (m/d)	0.003		Permeability coefficient in x direction (m/d)	0.002
	Permeability coefficient in y direction (m/d)	0.006		Permeability coefficient in y direction (m/d)	0.002
	Diffusion coefficient in x direction (m/d)	0.00012		Diffusion coefficient in x direction (m/d)	0.0008
	Diffusion coefficient in y direction (m/d)	0.00012		Diffusion coefficient in y direction (m/d)	0.001
Middle layer	Young's modulus (MPa)	3.8	Impermeable layer surrounding the landfill	Young's modulus (MPa)	21.5
	Poisson's ratio	0.26		Poisson's ratio	0.23
	Permeability coefficient in x direction (m/d)	0.2		Permeability coefficient in x direction (m/d)	0.0003
	Permeability coefficient in y direction (m/d)	0.4		Permeability coefficient in y direction (m/d)	0.0003
	Diffusion coefficient in x direction (m/d)	0.00038		Diffusion coefficient in x direction (m/d)	0.00002
	Diffusion coefficient in y direction (m/d)	0.00028		Diffusion coefficient in y direction (m/d)	0.00002

Using the conditions above, the simulation of landfill leachate polluting groundwater has been carried out and the results are shown in figs. 3, 4, 5 and 6.

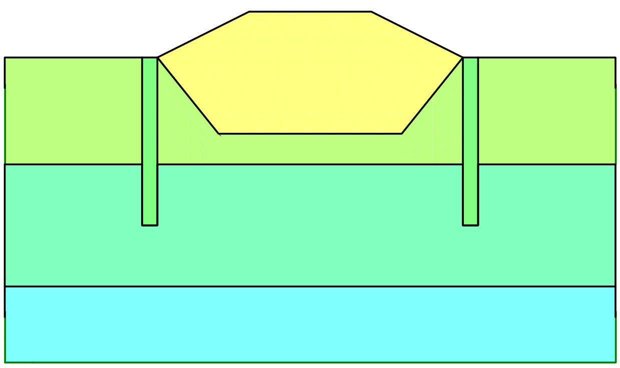

Figure 1. Landfill model

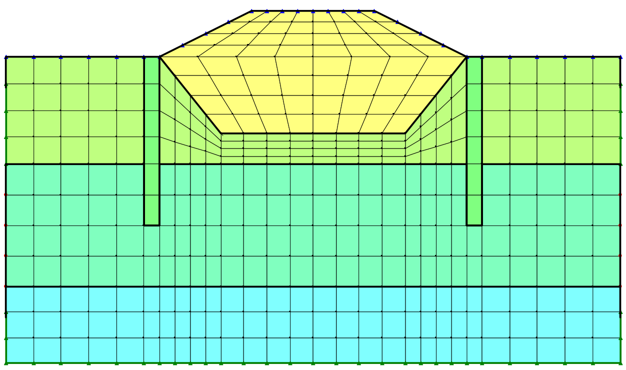

Figure 2. Finite element mesh

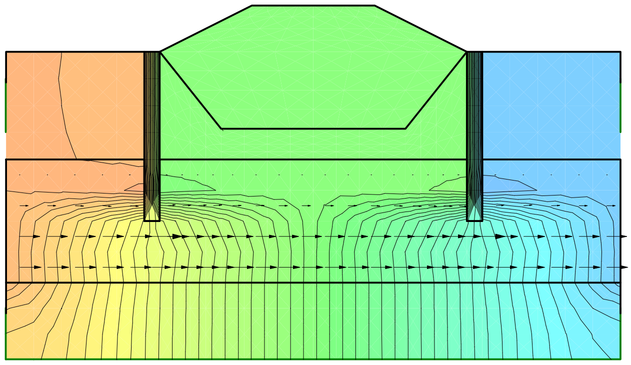

Figure 3. Seepage field without considering liquid-solid coupling

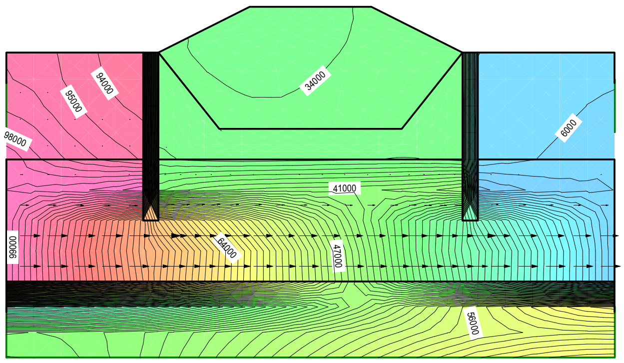

Figure 4. Seepage field considering liquid-solid coupling

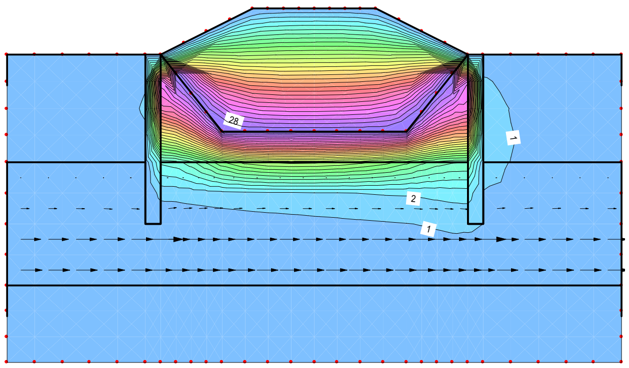

Figure 5. Concentration distribution without considering liquid-solid coupling

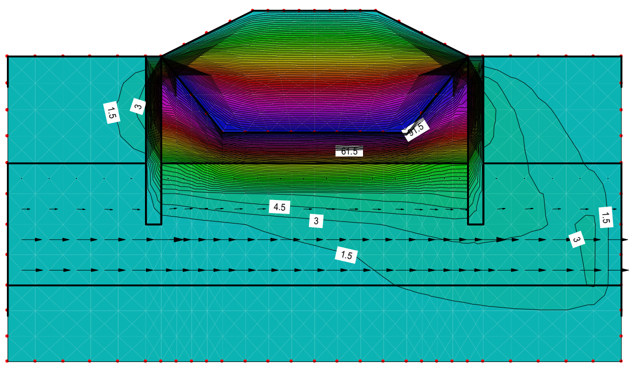

Figure 6. Concentration distribution considering liquid-solid coupling

From the distribution of the contours of contaminant concentrations in figs. (5) and (6), it can be concluded that extent of the contaminant plume and the contaminant concentrations derived considering coupled liquid-solid processes are larger than those derived without considering coupled liquid-solid process. This is because the groundwater seepage process affects the deformation of the porous media and with an increase in the groundwater head, the pore pressure is increased, which causes the pores and fractures in porous media to propagate and enlarge, thereby increasing the permeability coefficient. It goes without saying the increased permeability can accelerate the transport and migration process of contaminants.

CONCLUSIONS

In this paper, a mathematical model, which takes account of the coupling effect of deformation, was derived to describe landfill leachate polluting groundwater and the numerical method was applied to a hypothetical landfill to demonstrate the contaminating process quantitatively. The results showed that the contaminant plume and concentration derived using coupled liquid-solid processes are larger than those derived without considering coupled liquid-solid processes. Therefore, the validity of an environmental assessment of the impact of landfill leachate polluting groundwater cannot be guaranteed, if the liquid-solid coupling effect is not taken into account. The liquid-solid coupling effect may reflect the real processes of contaminant transport and the physical condition of the aquifer. A theoretical method has been presented for forecasting contaminant transport and for preventing and controlling contamination in the groundwater environment.

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