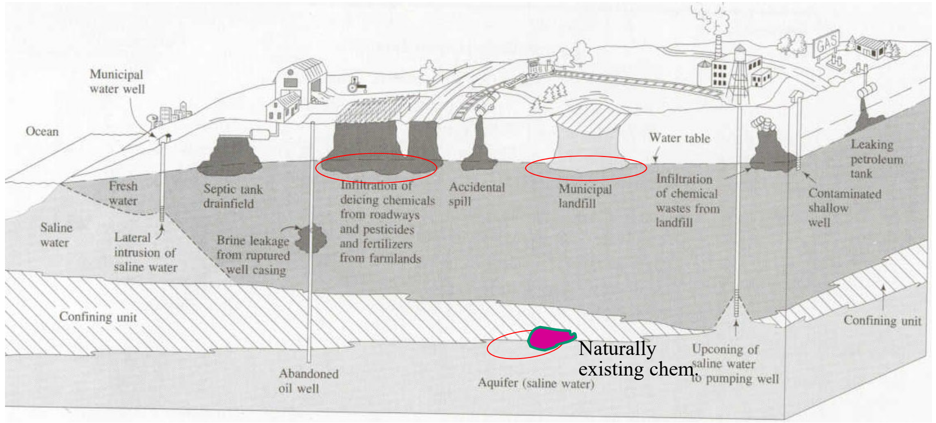
Contaminant Transport in Porous Media -Mechanism and Principles-

Mechanisms of ground and ground water contamination

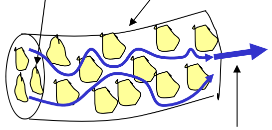


C.W.Fetter:" Contamination Hydrology", 1994

Flow in porous media (e.g., soils) in Traditional Geotechnical Engineering

ΔA:cross sectional area (void +soil grains)

Imaginary pipe



ΔQ:Flow rate (volume/time)

Darcy's velocity

or Advection（移流）

$v = -ki = \Delta Q/\Delta A$ (length/time)

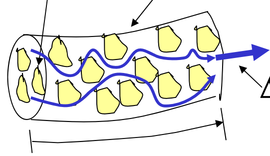
flow volume passing through unit area in unit time (流量速度)

not velocity of water molecule (水分子の速度ではない)

Flow in porous media (e.g., soils) in Environmental Geotechnics

ΔA:cross sectional area (void +soil grains)

Imaginary pipe



ΔQ:Flow rate (volume/time)

L: average length of water traveling in time *t*

not only Darcy's velocity but also

velocity of water molecule (or contaminant:汚染物質)

$v_{int} = L/t$

to evaluate the area and level of contamination

（汚染の範囲と濃度）

Derivation of basic equation on contaminant transport Advective - Dispersive Equation (移流−拡散方程式)

Modelling of miscible(混合する) contaminant (solute) transport in a porous media

in **one-dimensional conditions** (x-direction) for simplicity

terminology : (solute:溶質)　cf. solvent : 溶媒

hazardous species:汚染物質　　**e.g., water, chlorinated organic solvents**

definitions and assumptions(1)

•Porous media: a solid phase (soil grains) + a void space

The void is **fully saturated** by fluid phase (water)

完全飽和 **(Sr=100%)**

•The contaminant is **fully soluble** in the fluid phase

完全溶解

•Concentration of contaminant (solute) in the **fluid phase**:

濃度C= **mass of contaminant in unit volume of pore fluid**

汚染物質の質量 ／単位間隙流体定積

(*unit:mg/l, g/m*^{3})

Not unit volume of soil (fluid+solid phases)

definitions and assumptions(2)

•Concentration of contaminant (solute) held (adsorbed : 吸着した) on **solid phase**: 土粒子に吸着した汚染物濃度

C_s = **mass of contaminant in unit mass of soil grain**

汚染物質の質量　／単位土粒子質量　(*unit: g/kg,mg/kg*)

•**Non-reactive (conservative) contaminant**:生化学反応無し

no chemical and biological reactions,

no affinity(親和性) for solid phase,

the mass of contaminant is conserved in the fluid phase.

液層の汚染物質は保存される

definitions and assumptions(3)

•**Scale considered**

Microscopic scale: processes at the “pore size” scale ***grain size***

Mesoscopic scale: processes at the “laboratory (***specimen***)” scale

Macroscopic scale: processes at the “***field***” scale

Transport Processes

①Advection（移流）

②Molecular Diffusion（分子拡散)

③Mechanical Dispersion（機械的分散)

①Advection(convection)

Transport of solute with the average velocity of fluid flow

Driving force : "hydraulic gradient" 動水勾配

v_{int} : average velocity of fluid flow or interstitial velocity in the direction of x 間隙内平均流速（参照方向：ここではx方向）

(Distance of travel of (average) solute (L) in time t: L= $v_{int} \cdot t$)

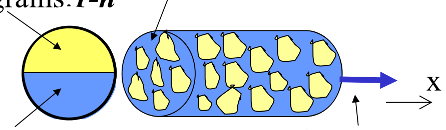
Darcy's seepage velocity

$$v_{\text{int}} = \frac{\Delta Q}{\Delta A n} = \frac{v}{n} \quad (1)$$

porosity

$$n = \frac{e}{1+e}$$

Void ratio



Cross sectional area available for seepage

$n\,\Delta A < \Delta A \rightarrow v_{int} > v$

Advective mass flux : J_A

$$J_A = n\, v_{int}\, C \qquad (2)$$

Mass flux:

mass of solute flowing through a unit cross-sectional area of soil per unit time (*including solid phase*)

②Molecular diffusion

Diffusion: transport of a solute in response to a gradient in its concentration

Driving force is "**chemical gradient**" : $\partial C / \partial x$

濃度勾配

Fick's first law:

Diffusive mass flux in solution: J_D

$$J_D = -D_0 \frac{\partial C}{\partial x} \qquad (3)$$

D_0: *free water* diffusion coefficient （無限希釈水中）

[L²/T] ex) m²/sec → $[L^2/T]$ ex) m^2/sec

not dependent on concentration but temperature, being 50% less at 5°C than at 25°C

P1-2 for Detail Shackelford & Daniel (1991)

What's going on in a soil??

Diffusive mass flux in soil: J_D

apparent one: Shackelford & Daniel (1991)

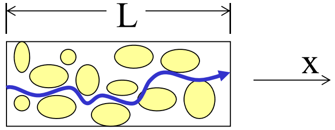
$$J_D = -\tau_a D_0 n \frac{\partial C}{\partial x} \quad (4)$$

or

$$J_D = -D_m n \frac{\partial C}{\partial x} \quad (5)$$

τ_a :tortuosity factor (屈曲度)

D_m:effective diffusion coefficient (有効分子拡散係数) $[L^2/T]$



Length of real flow path: $L_e > L$

Tortuosity(曲がりくねり)

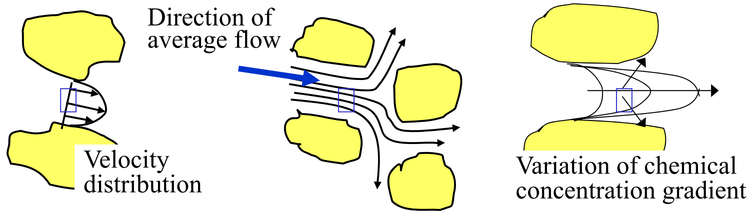
$$\tau = f\left(\frac{L}{L_e}\right) = \left(\frac{L}{L_e}\right)^2 \; or \left(\frac{L}{L_e}\right) \quad (6)$$

depending on grading ($D_c = D_{60}/D_{10}$) ➡ uniform (small D_c) →large τ ≒ 0.7; well graded (large D_c) →small τ 0.5-0.01

Uniformity Coef.(均等係数)

P1-2

③Mechanical Dispersion



Mechanisms of mechanical dispersion in mesoscopic scale

In microscopic scale, phenomenon of mesoscopic mechanical dispersion does not exist. Thus the mesoscopic MD arises as a result of the averaging of phenomena from the microscopic(pore) scale to the mesoscopic (laboratory) scale. ミクロスケールには機械的分散なし

Macroscopic(field) scale mechanical dispersion is caused by variations in mesoscopic flow velocities. (<=*heterogeneity*)

マクロスケールの分散<=メソスケールの不均質性

Dispersive mass flux: J_M

$$J_M = -D_L n \frac{\partial C}{\partial x} \quad (7)$$

D_L:mechanical dispersion coefficient (機械的分散係数) $[L^2/T]$

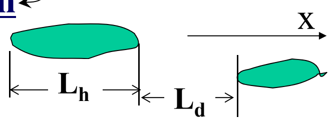
D_L : not const. but f(v_{int})

$$D_L = \alpha_L v_{int}^{\beta} \quad (8)$$

α_L:longitudinal dispersivity (縦方向分散係数)

β = 1〜2 (for practice) = 1

α_L [L]← heterogeneity of medium

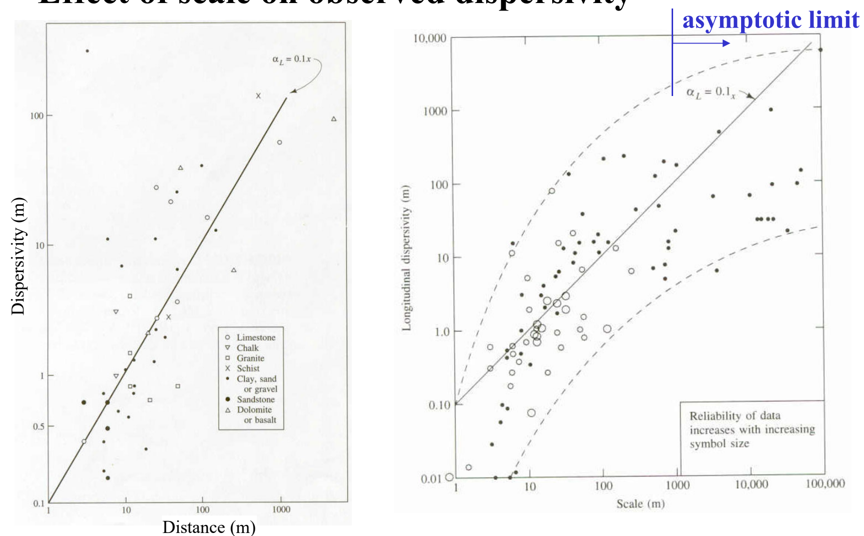


•macroscopic scale: $\alpha_L \sim L_h$ or L_d

•mesoscopic scale: $\alpha_L \sim D_{50}$ (uniform, homogeneous material)

α_L depends on size of region of consideration ***P1-1***

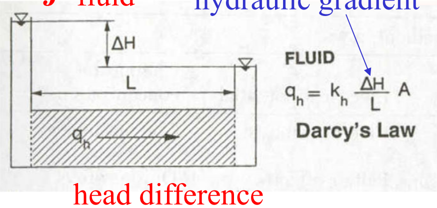
Effect of scale on observed dispersivity



Field measured values of longitudinal dispersivity as a function of the scale of measurement; "Contaminant Hydrology" Fetter, 1999

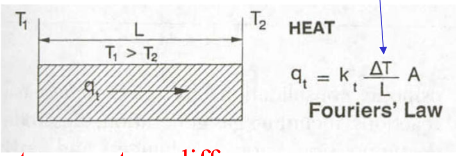
Coupled Flow Processes

J=fluid   hydraulic gradient



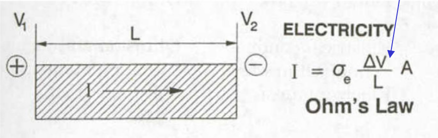
head difference

J=heat   thermal gradient



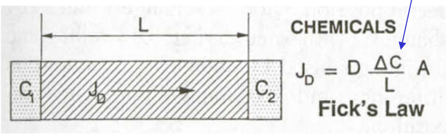
temperature difference

J=electric current   electrical gradient



electric potential difference

J=chemical ion   chemical gradient



concentration difference

Coupled Flow Processes

Flow is not independent on other driving force.

$$J_i = L_{ij} X_i$$

L_{ij}:coupling coefficients

Flow J_i	Gradient X_i			
	Hydraulic head	Temperature	Electrical	Chemical Concentration
Fluid	Hydraulic conduction: Darcy's law	Thermo-osmosis	Electro-osmosis	Chemical osmosis
Heat	Isothermal heat transfer	Thermal conduction: Fourier's law	Peltier effect	Dufour effect
Current	Streaming current	Thermo-electricity Seebeck effect	Electric conduction: Ohm's law	Diffusion and membrane potentials
Ion	Streaming current	Thermal diffusion Soret effect	Electro-phoresis	Diffusion: Fick's law

In general, coupled flow are ignored in the formulation of a solute transport, because these processes tend to be insignificant. *Exception: disposal of heat generating or radioactive waste.*

Practical ranges of flow parameters for fine-grained saturated soils

Parameters	Minimum	maximum
Porosity, n	0.1	0.7
Hydraulic conductivity, k_h(m/s)	1 x 10^{-11}	1 x 10^{-4}
Thermal conductivity, k_t(W/mK)	0.25	1.0
Electrical conductivity, σ_e(S/m) σ_e=1/ρ (ρ:resistivity (ohm-m)	0.01	1.0
Electro-osmotic conductivity,k_e (m²/sV)	1 x 10^{-9}	1 x 10^{-8}
Diffusion coefficient, D_m (m²/s)	1 x 10^{-11}	1 x 10^{-9}

Combined Processes

In the absence of coupled flow process,

Total mass flux of a solute species:***J***

$$J = J_A + J_D + J_M \quad (9)$$

Eqs. (3),(5) and (7)

$$J = nv_{\text{int}} C - D_m n \frac{\partial C}{\partial x} - D_L n \frac{\partial C}{\partial x} \quad (10)$$

or

$$J = nv_{\text{int}} C - D_{hl} n \frac{\partial C}{\partial x} \quad (11)$$

Hydrodynamic dispersion coefficient (流体力学的分散係数)

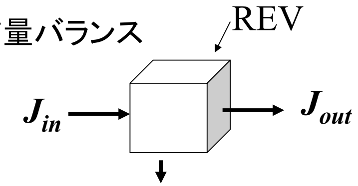
$$D_{hl} = D_m + D_L = \tau D_0 + \alpha_L v_{\text{int}} \quad (12)$$

,because the two phenomena cannot be separated in measurement.

Contaminant transport equation

Balance of contaminant mass within an Representative Elementary Volume(REV)

参照要素の質量バランス



Reaction if occurred

増加速度		流入量		流出量		化学反応等による変化
Rate of solute mass increase within REV	=	**Solute mass flux into the REV (J_{in})**	-	**Solute mass flux out of the REV (J_{out})**	+	**Increase or decrease of solute mass due to various reactions**

Contaminant transport equation cont.

total mass(adsorbed on solid phase+ dissolved in fluid phase)

general mass balance eq.

$$\frac{\partial m}{\partial t} = -\nabla J \pm R \pm \lambda m \quad (13)$$

∇: $\partial/\partial x + \partial/\partial y + \partial/\partial z$

R: chemical reaction

λ: a general rate constant in radio active and/or biological decay(半減期)

For 1-D flow

$$\frac{\partial(nC)}{\partial t}+\frac{\partial((1-n)\rho_s C_s)}{\partial t}=-\frac{\partial}{\partial x}\left(n v_{int} C - D_{hl} n \frac{\partial C}{\partial x}\right) \pm R \pm \lambda\left(nC+(1-n)\rho_s C_s\right) \quad (14)$$

Adsorption（on solid phase：固相中）

In fluid phase：液相中

Homework(2) Due28th June

From mass balance in REV, derive eq.(13) and (14)
Show the details of derivation.

Advective-Dispersive Equation 移流−拡散方程式

Simplified version of eq.(14)

with the following assumptions

① no chemical, biological reaction

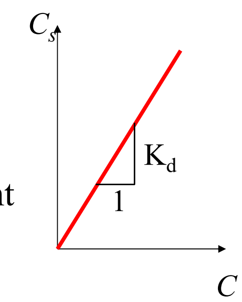
② porous medium is rigid

③ steady state flow (v_{int}:const)

④ C_s/C: const=K_d:

linear equilibrium adsorption coefficient

（分配係数） ***partitioning coefficient***



＋ eq.(14)

Advective-Dispersive Equation

$$R_d \frac{\partial C}{\partial t} = D_{hl} \frac{\partial^2 C}{\partial x^2} - v_{\text{int}} \frac{\partial C}{\partial x} \quad (15)$$

Coefficient of retardation
（遅延係数）

$$R_d = 1 + \frac{(1-n)\rho_s K_d}{n} \quad (16)$$

For a solute species which is adsorbed onto the solid grains: $K_d > 0 \rightarrow R_d > 1$

For a non-adsorbing solute species: $K_d = 0 \rightarrow R_d = 1$

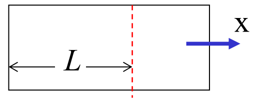
Solutions of Advective-Diffusive equation

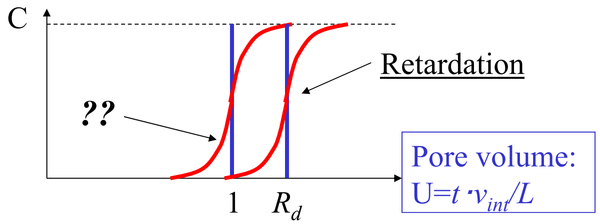
Non reactive, linear equilibrium adsorption

$$R_d \frac{\partial C}{\partial t} = D_{hl} \frac{\partial^2 C}{\partial x^2} - v_{\text{int}} \frac{\partial C}{\partial x} \quad (15)$$

Coefficient of retardation $R_d = 1 + \frac{(1-n)\rho_s K_d}{n}$

Breakthrough curve:
Variation of *C*
at an observation point
(*L from boundary)*

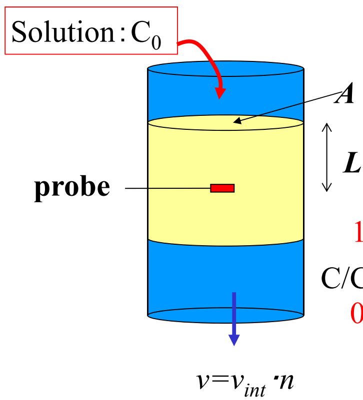




Pore volume: *U*

Column test

One pour volume=***ALn***

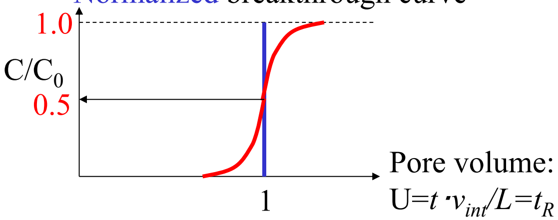


Total discharge

$$U = \frac{v_{\text{int}} n A t}{A L n} = \frac{v_{\text{int}} t}{L} = t_R \quad (17)$$

Dimensionless time

Normalized breakthrough curve



Solutions of diffusive equation
拡散方程式の解法

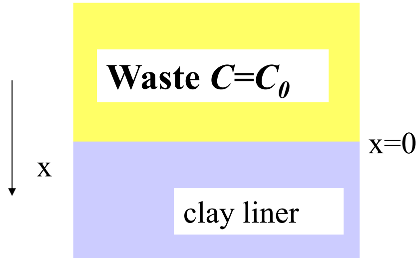
Fick's second law:
フィックスの第二法則

$v_{int} = 0 \rightarrow$ eq.(15)

$$\frac{\partial C}{\partial t} = D_m \frac{\partial^2 C}{\partial x^2} \quad (18)$$

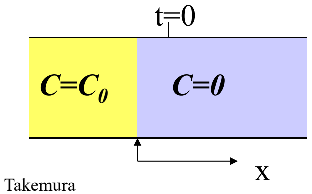
(1) condition 1

B.C. $C(0,t) = C_0$
I.C. $C(x,0) = 0$ (19)



(2) condition 2

No B.C.
I.C. $C(x,0)=0 \quad x>=0$
$=C_0 \quad x<0$ (20)



(1) solusion1

Technique:

Laplace or Fourier transform

PD →OD

$$C(x,t) = C_0 erfc\frac{x}{2(D_m t)^{0.5}} \quad (21)$$

erfc(x): Complementary error function: tabulated in text book.

余誤差関数 $erfc(B) = 1 - erf(B) \qquad erfc(-B) = 1 + erf(B) \qquad$ (i)

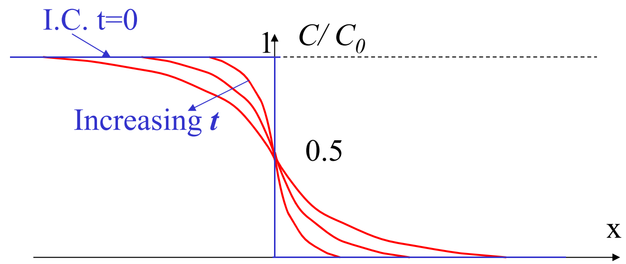
誤差関数 $erf(B) = \frac{2}{\sqrt{\pi}}\int_0^B e^{-t^2}dt \approx \sqrt{1-\exp\left(\frac{-4B^2}{\pi}\right)} \qquad$ (ii)

$= 1$ for B=3 or greater

$0 \le erfc(B) \le 2$

(2) solusion2

$$C(x,t) = \begin{cases} \frac{1}{2}C_0\left[1 + erf\frac{-x}{2(D_m t)^{0.5}}\right] & (x<0) \\ \frac{1}{2}C_0 erfc\frac{x}{2(D_m t)^{0.5}} & (0 \le x) \end{cases} \quad (22)$$



Error function and probability integral Φ

$$erf(B) = \frac{2}{\sqrt{\pi}}\int_0^B e^{-t^2}dt \quad \text{(ii)} \qquad \Phi(B) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^B e^{-w^2/2}dw \quad \text{(iii)}$$

$t = w/\sqrt{2}$

$$erf(B) = \frac{2}{\sqrt{2\pi}}\int_0^{\sqrt{2}B} e^{-w^2/2}dw \quad \text{(iv)}$$

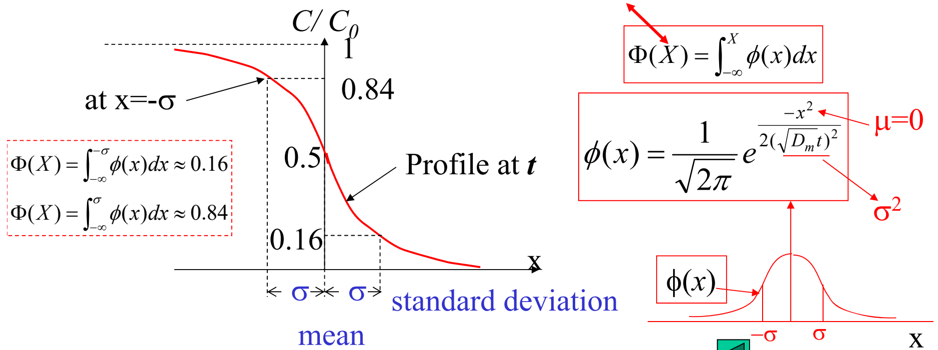
From (iii),(iv)

$$erf(B) = 2\Phi\left(\sqrt{2}B\right) - 1$$
$$erfc(B) = 2 - 2\Phi\left(\sqrt{2}B\right) \quad \text{(i')}$$

Eq. (22)

Profile of concentration for condition 2

$$C(x,t) = \begin{cases} \frac{1}{2}C_0\left[1 + erf\frac{-x}{2(D_m t)^{0.5}}\right] = C_0\Phi\left(\frac{-x}{(2D_m t)^{0.5}}\right) & (x<0) \\ \frac{1}{2}C_0 erfc\frac{x}{2(D_m t)^{0.5}} = 1 - \Phi\left(\frac{x}{(2D_m t)^{0.5}}\right) & (0 \le x) \end{cases} \quad (22')$$



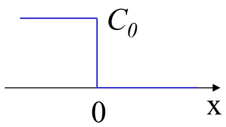
Solutions of A-D equation

P.D.E $\frac{\partial C}{\partial t} = D_{hl}\frac{\partial^2 C}{\partial x^2} - v_{\text{int}}\frac{\partial C}{\partial x}$ (23) $R_d=1 \rightarrow$ eq(15)

B.C.:Nothing

I.C. $C(x,0)=1-H(x)$

Heaviside func.
$H(x)=0$ $(x<0)$
1 $(x>=0)$ } (20)



Technique:

Transformation of independent variables:

$\xi = x - v_{\text{int}}t$
$\tau = t$ } (24)

P.D.E $\frac{\partial C}{\partial \tau} = D_{hl}\frac{\partial^2 C}{\partial \xi^2}$ (25)

I.C. $C(\xi, 0)=1-H(\xi)$ (26)

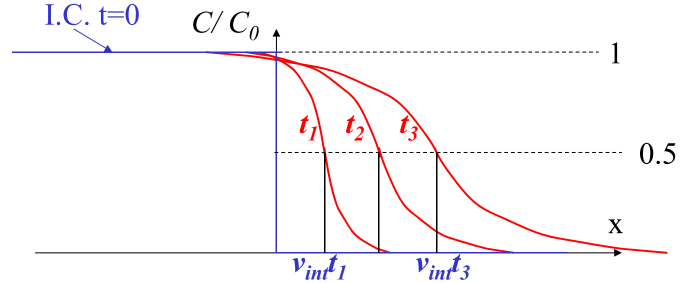
Same as con.(2) for D.eq.s (18,20)

Laplace, Fourier transform

Solution of A-D equation with simple condition

$$C(x,t) = \frac{1}{2}C_0\left[1+erf\left(\frac{v_{\text{int}}t-x}{2(D_{hl}t)^{0.5}}\right)\right] \quad (v_{\text{int}}t > x)$$

$$\frac{1}{2}C_0 erfc\left(\frac{x-v_{\text{int}}t}{2(D_{hl}t)^{0.5}}\right) \quad (v_{\text{int}}t \le x) \quad (27)$$



Solutions of A-D equation with various B.C.

See Handout 2

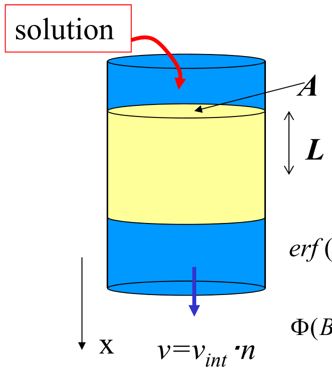
Determination of D_{hl}

see p2-2,p2-3

Approx. solution:

Column test

$$C(x,t) = \frac{1}{2}C_0 erfc\left(\frac{R_d x - v_{\text{int}}t}{2(R_d D_{hl}t)^{0.5}}\right) \quad (28)$$



$$\left(\frac{x - v_{\text{int}}t/R_d}{2(D_{hl}t/R_d)^{0.5}}\right)$$

mean

$\sqrt{2}\sigma$

$$erf(B) = \frac{2}{\sqrt{\pi}}\int_0^B e^{-t^2}dt$$

$$\Phi(B) = \frac{1}{\sqrt{2\pi}}\int_{-\infty}^{B} e^{-w^2/2}dw \rightarrow \left[-\frac{(x-\mu)^2}{2\sigma^2}\right]$$

Determination of D_{hl} *(contn.)*

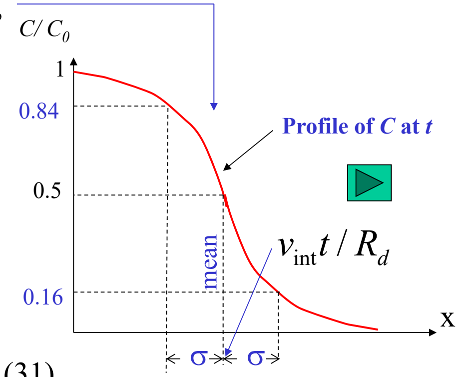
At given t, x being the variable,

$$\sigma = (2D_{hl}t/R_d)^{0.5} \quad (29)$$

$$x_{C/C_0=0.16} - x_{C/C_0=0.84} =$$

$$2\sigma = 2(2D_{hl}t/R_d)^{0.5} \quad (30)$$

$$D_{hl} = \frac{\left(x_{C/C_0=0.16} - x_{C/C_0=0.84}\right)^2}{8t} \quad (31)$$



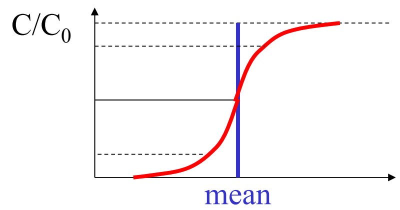
At given x, t being the variable → Same technique can be applied
(**breakthrough curve**)

Homework (3):Due 2nd July

$$D_{hl} = \frac{\left(x_{C/C_0=0.16} - x_{C/C_0=0.84}\right)^2}{8t} \quad (31)$$

Derive equation of D_{hl} (similar to eq.(31)) using breakthrough curve.

At given x(or L), *t* being the variable,



Pore volume:
$U = t \cdot v_{int}/L = t_R$

A-D Equation in 3D

general mass balance eq. $\partial/\partial x + \partial/\partial y + \partial/\partial z$

$$J = nv_{int}c - D_{hl}n\frac{\partial C}{\partial x} \quad (11)$$

$$\frac{\partial m}{\partial t} = -\nabla J \pm R \pm \lambda m \quad (13)$$

$R \pm \lambda m$ → 0 : conservative condition

$$R_d\frac{\partial C}{\partial t} = \left[\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)\right]$$

$$-\left[\frac{\partial}{\partial x}(v_xC) + \frac{\partial}{\partial y}(v_yC) + \frac{\partial}{\partial z}(v_zC)\right] \quad (13')$$

v_x, v_y, v_z : **Interstitial velocity in x,y,z direction**

D_x, D_y, D_z : **Hydrodynamic dispersivity in x,y,z direction**

?

Dispersivity in 3D problems

Non-homogeneous, anisotropic soil

Second rank symmetrical tensor of mechanical dispersion coefficient

$$D_{ij} = a_{ijkm}\frac{v_kv_m}{v}f(P_e,\delta) \quad (32)$$

ij:microscopic porous matrix configuration
km: velocity

***P_e*:Peclet number:**

$$P_e = \frac{L \cdot v}{D_0} \quad (33)$$

L:characteristic length: d_{50}
v: interstitial average velocity

$f(P_e, \delta)$: function introducing the effect of molecular diffusion

δ: ratio of L to the length characterizing the cross section of pore

a_{ijkm}:Four rank tensor in 3D: 81 components
2D:16 components

In homogenous medium

D_{ij} is not constant because D_{hl} is a function of v.

In case of f(P_e, δ)=1

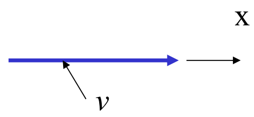
$a_{ijkm} \rightarrow a_L, a_T$ — Longitudinal & Transverse dispersivity

$$D_{ij} = a_T v \delta_{ij} + (a_L - a_T)(v_i v_j / v) \quad (34)$$

Kronecker delta

x-axis:direction of stream line

$$[D_{ij}] = \begin{bmatrix} a_L v & 0 & 0 \\ 0 & a_T v & 0 \\ 0 & 0 & a_T v \end{bmatrix} \quad (35)$$



2D A-D equation in homogeneous medium with uniform velocity in x direction

Cartesian coordinates

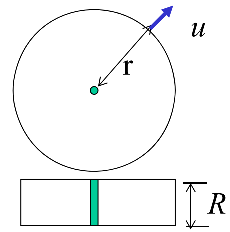
$$\frac{\partial C}{\partial t} = D_L \frac{\partial^2 C}{\partial x^2} + D_T \frac{\partial^2 C}{\partial y^2} - v_x \frac{\partial C}{\partial x} \quad (36)$$

Radial flow from a well in cylindrical coordinates

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial r}\left(D \frac{\partial C}{\partial r}\right) + \frac{D}{r}\frac{\partial C}{\partial r} - u \frac{\partial C}{\partial r} \quad (37)$$

average pore velocity of injection

$$u = \frac{Q}{2\pi n R r}$$



Q:rate of injection

Homework(4) Due 3rd July

From eq(13'), derive eq.(37).

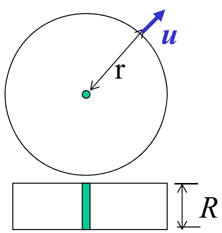
$$R_d \frac{\partial C}{\partial t} = \left[\frac{\partial}{\partial x}\left(D_x \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial y}\left(D_y \frac{\partial C}{\partial y}\right) + \frac{\partial}{\partial z}\left(D_z \frac{\partial C}{\partial z}\right)\right] - \left[\frac{\partial}{\partial x}(v_x C) + \frac{\partial}{\partial y}(v_y C) + \frac{\partial}{\partial z}(v_z C)\right] \quad (13')$$

Radial flow from a well in polar coordinates

$$\frac{\partial C}{\partial t} = \frac{\partial}{\partial r}\left(D \frac{\partial C}{\partial r}\right) + \frac{D}{r}\frac{\partial C}{\partial r} - u \frac{\partial C}{\partial r} \quad (37)$$

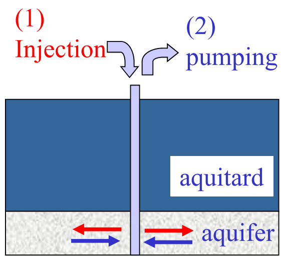
average pore velocity of injection

$$u = \frac{Q}{2\pi n R r}$$



Q:rate of injection

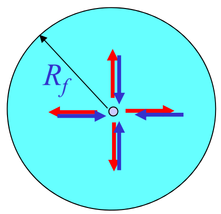
Single well tracer test



(1)Injection of water with a conservative tracer into an aquifer via a well.

(2)The subsequent pumping of the well to recover the injected fluid.

The fluid velocities of the water pumped and injected are much greater than the natural GWF.
Eq. (37) can be rewritten as,



$$D = \alpha_L u + D_m \quad (12)$$

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial r} = \alpha_L u \frac{\partial^2 C}{\partial r^2} + \frac{D_m}{r}\frac{\partial}{\partial r}\left(r \frac{\partial C}{\partial r}\right) \quad (38)$$

Single well tracer test, cont.

The solution of eq.(38) for the withdrawal phase of an injected-withdrawal well test, in which the diffusion term in eq.(12) is neglected, was given by Gelhar and Collins(1971) .

$$\frac{C}{C_0}=\frac{1}{2}C_0 erfc\left(\frac{(U_p-U_i)-1}{\left\{\frac{16}{3}(\alpha_L/R_f)\left[2-(1-U_p/U_i)\right]^{1/2}\left[1-U_p/U_i\right]\right\}^{1/2}}\right) \quad (39)$$

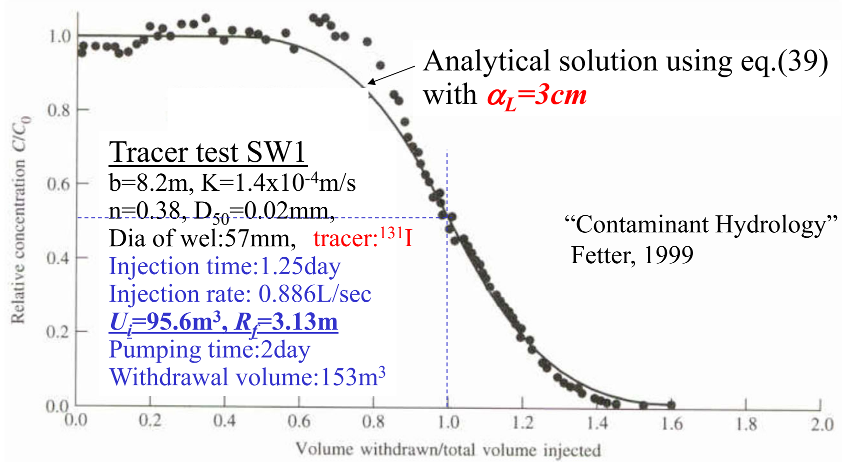
U_p:cumulative volume of water withdrawal during various times
U_i:total volume of water injected during the injection phase
R_f:average frontal position of the injected water at the end of the injection period, which is defined by

$$R_f=\left(\frac{Qt}{\pi bn}\right)^{1/2} \quad (40)$$

Where Q=rate of injection, t= total time of injection, b=aquifer thickness, n=porosity

Comparison of measured C/C_0 for a single-well injection-withdrawal test vs. analytical solution

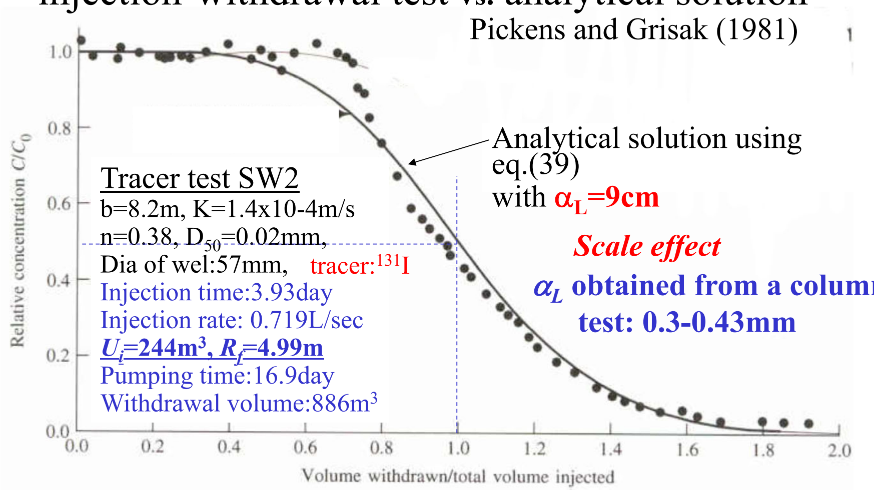
Pickens and Grisak (1981)



"Contaminant Hydrology" Fetter, 1999

Comparison of measured C/C_0 for a single-well injection-withdrawal test vs. analytical solution

Pickens and Grisak (1981)



Scale effect

α_L obtained from a column test: 0.3-0.43mm

"Contaminant Hydrology" Fetter, 1999

Longitudinal and transverse dispersivity

a_L / a_T **control the shape of a contaminant plume in 2D mass transport** ***P1-4,5***

No theoretical derivation but field observations

$$a_L/a_T = 6 - 20$$

Effect of diffusion in D_{hl}

From column test(Bear and Bachmat,1967)

$$f(P_e,\delta)=\frac{P_e}{2+P_e+4\delta^2} \quad (38) \qquad P_e=\frac{d_{50}\cdot v_{\text{int}}}{D_0}$$

P1-4

Zone I: molecular diffusion predominates.
(Pe < 0.4)

Zone II:effects of mechanical dispersion and molecular diffusion are of the same order of magnitude.
(0.4<Pe < 5)

Zone III:the spreading is caused by mainly mechanical dispersion. $D_{hl}/D_0=\alpha(P_e)^m,\ \ \alpha\approx 0.5 \ \ 1<m<1.2$

Effect of diffusion in D_{hl} *(cont.)*

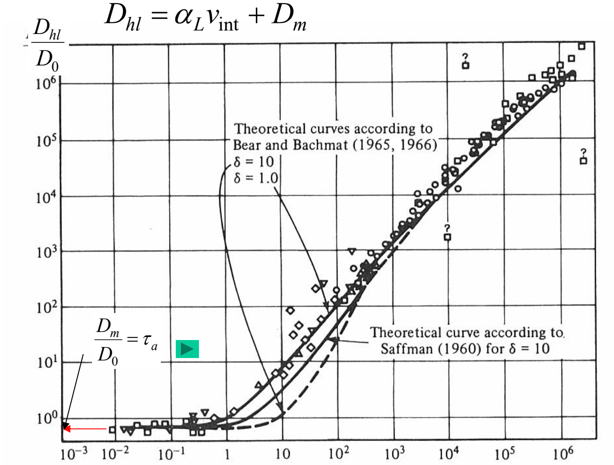
Zone IV: mechanical dispersion predominates in the range of validity of Darcy's law, except of a factor governing the transversal dispersion.

Why!!

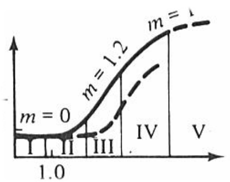
Zone V:pure mechanical dispersion, but beyond the range of Darcy's law. Effect of inertia and turbulence can be no longer neglected.

Relationship between molecular diffusion and longitudinal hydrodynamic dispersion

$$D_{hl}=\alpha_L v_{\text{int}}+D_m$$

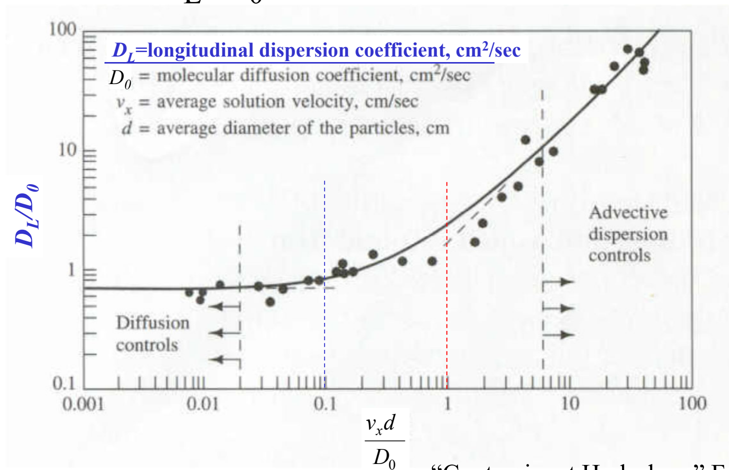


$P_e=\frac{v_x d}{D_0}$



Bear & Verruijt (1990)

Dimensionless dispersion coefficient D_L/D_0 vs. Peclet number



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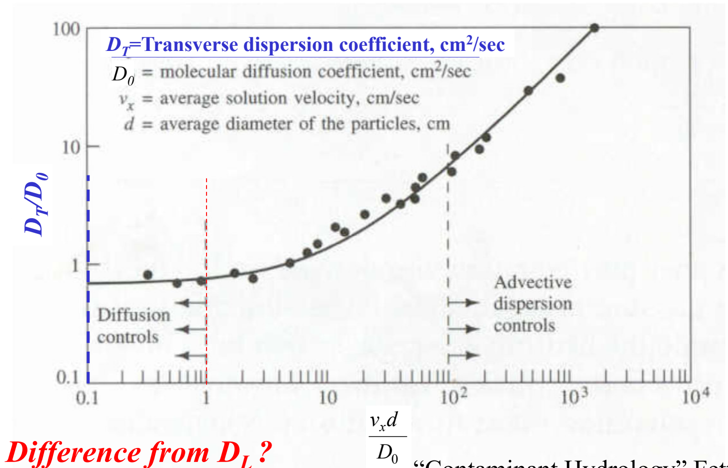
Dimensionless dispersion coefficient D_T/D_0 vs. Peclet number



Difference from D_L ?

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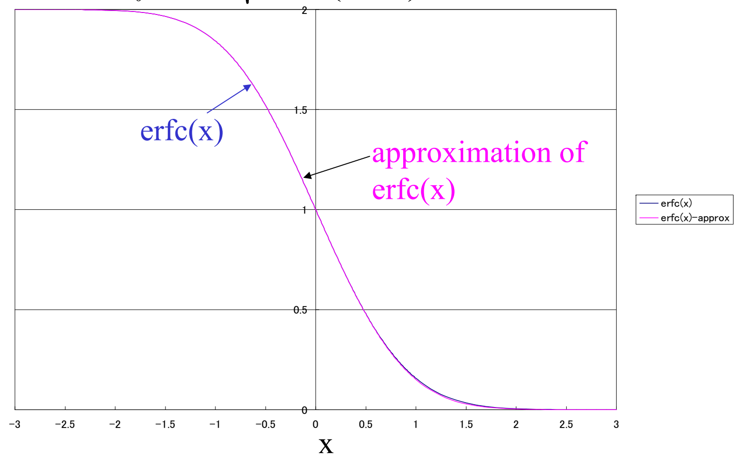
Complementary error function

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x e^{-t^2}dt \approx \sqrt{1-\exp\left(\frac{-4x^2}{\pi}\right)}$$

$$erfc(x) = 1 + erf(x) \quad x \le 0$$
$$erfc(x) = 1 - erf(x) \quad x \succ 0$$



1st announcement on Group Work

4 groups (Four or five students each group)

1st objective: Problem statement or finding in environmental issues in your own county and similar one in Japan;
Similarity and Difference

2nd objective: Summary of Key issues to solve the problems
specific conditions in the country/ the experiences in other country including Japan/ technological action/ legal action

Group work in the lecture time of July 16 and 19 + additional group work
Presentation: August 2nd

Submitted material: PPT files for presentation and written report for each objective

Last Year Common problems:Toyosu new market

Working Groups

Group	ID	Name	call name	lab	country	
1	18M58220	TSAKEUCHI katsuyuki	Takeuchi	Takemura	Japan	
1	18M58348	SHAFI S M	Shafi	Takemura	Bnagladesh	
1	19M51183	ITOH Yusaku	Itoh	Takahashi	Japan	
1	19M51243	KATO Masaki	Katoh	Niwa	Japan	
1	19M51438	HU Lihang	Hu	Kasama	China	
1	19M51450	WANG Yuankai	Wang	Takahashi	China	
2	18M58414	ZHANG HAO QIONG	Choo	Takemura	China	
2	19M51160	AKAGI Keisuke	Akagi	Kitazume	Japan	
2	19M51177	ADACHI Keigo	Adachi	Yohimura/Fujii	Japan	
2	19M51190	INOUE Tamaki	Inoue	Takahashi	Japan	
2	19M51421	ZHANG Lao	Zhang	Kasama	China	
2	19R51501	BERGMAN Hanna	Hanna	Niwa	Sweden	
3	18M58294	LAO Yilun	Lao	Takemura	China	
3	18M58325	LI Xuechun	Li	Hirose	China	
3	19M51208	IMAI Hideyuki	Imai	Kitazume	Japan	
3	19M51295	TAKAYAMA Shinichiro	Takayaam	Kasama	Japan	
3	19M51326	TOTSUKA Shutaro	Totsuka	Sasaki	Japan	
3	19M51415	WAKAYAMA Hiroki	Wakayama	Niwa	Japan	