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The effect of temperature on the seepage transport of suspended particles

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1 Introduction

◆ 污染物的迁移是岩土工程领域一个重要课题

Water quality issues associated with contaminant transport in porous media.

◆ 对于可溶性离子，随水流直接进行渗透迁移

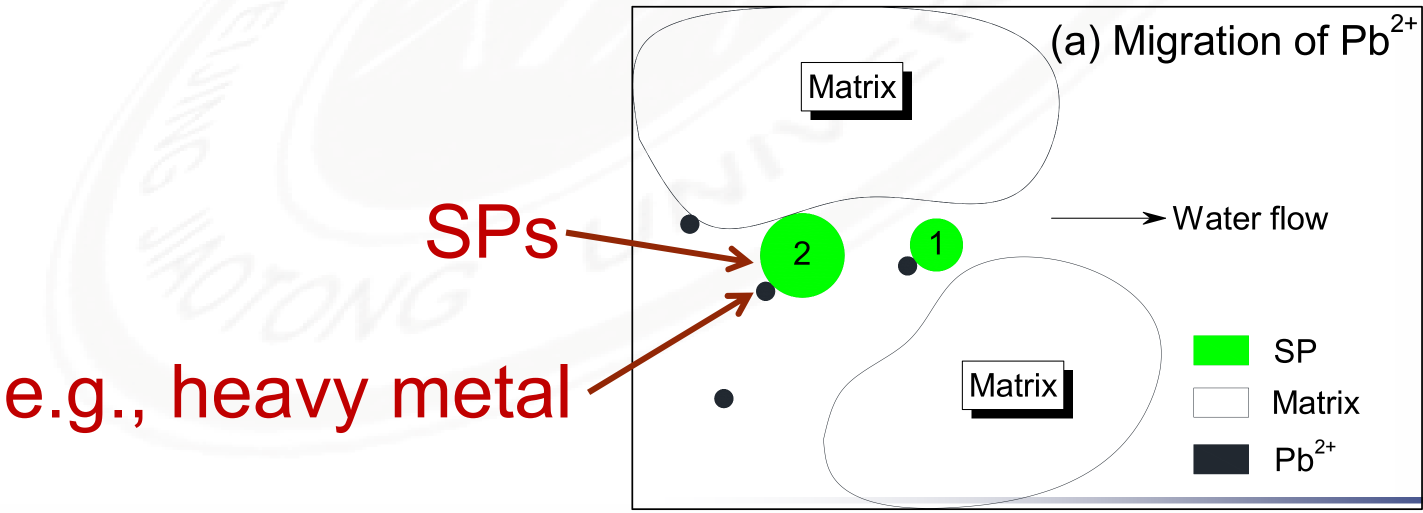
(碱离子、放射性物质、重金属离子)

Dissolved ions can migrate with seepage water

(alkaline ions, radioactive substances, and heavy metal ions, etc.).

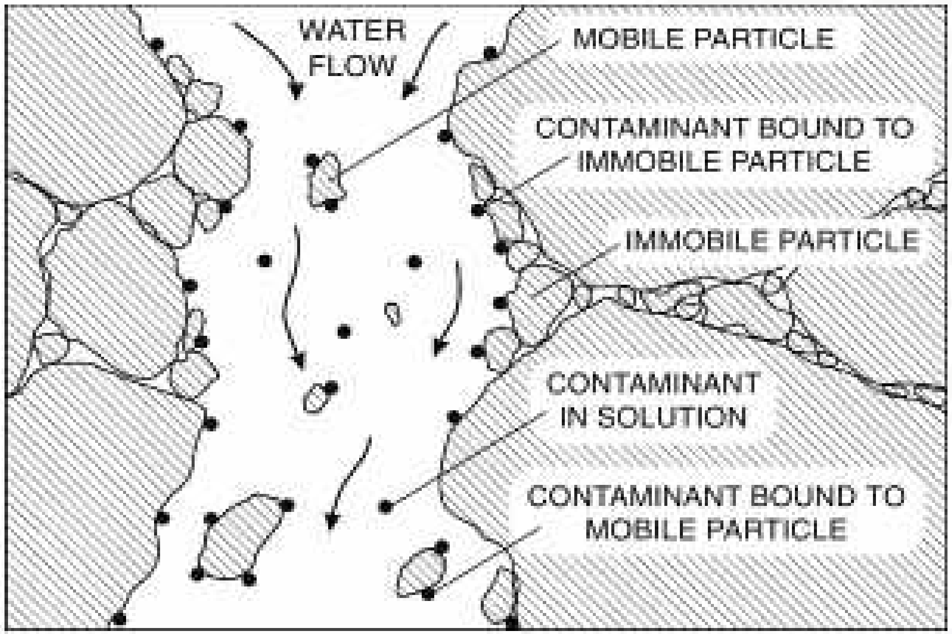
◆ 实际上, 大尺度悬浮颗粒(>1 μm)对污染物(如重金属)有高的吸附能力

In fact, suspended particles (SPs, >1 μm in size) have a high capacity to absorb pollutants (e.g., heavy metal) and move with water.



◆ 悬浮颗粒可以促进污染物的迁移,起着第3相的作用(液相、不移动固相、移动固相)

SPs can also facilitate the transport of contaminants, and act as a third phase.



- liquid phase
- immobile solid phase
- mobile solid phase

- 目前，悬浮颗粒的渗透迁移已有大量工作

  At present, there are many researches on the seepage transport of SPs.

- 然而，温度效应的影响只有很少研究

  Little research has been conducted on the effect of temperature for large-sized SPs.

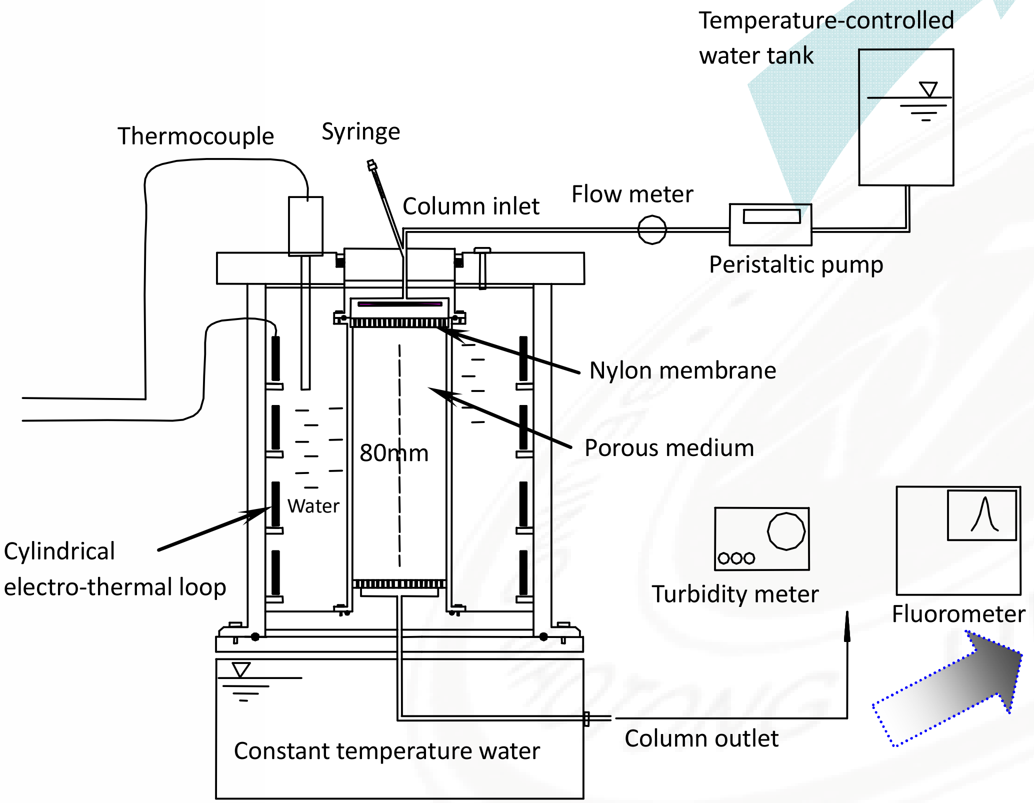
- 目标：研究温度效应

  The purpose is to investigate temperature effect.

2 Materials and methods

- Sand column test
- Pulse-injection pattern: 2s
- 2 velocities: v=0.066, 0.199 cm/s
- Particle concentration: C_{inj}=0.8 mg/ml
- Temperature: T=15, 35, 55 °C

Temperature-controlled experimental apparatus



Peristaltic pump：

Turbidity meter ：

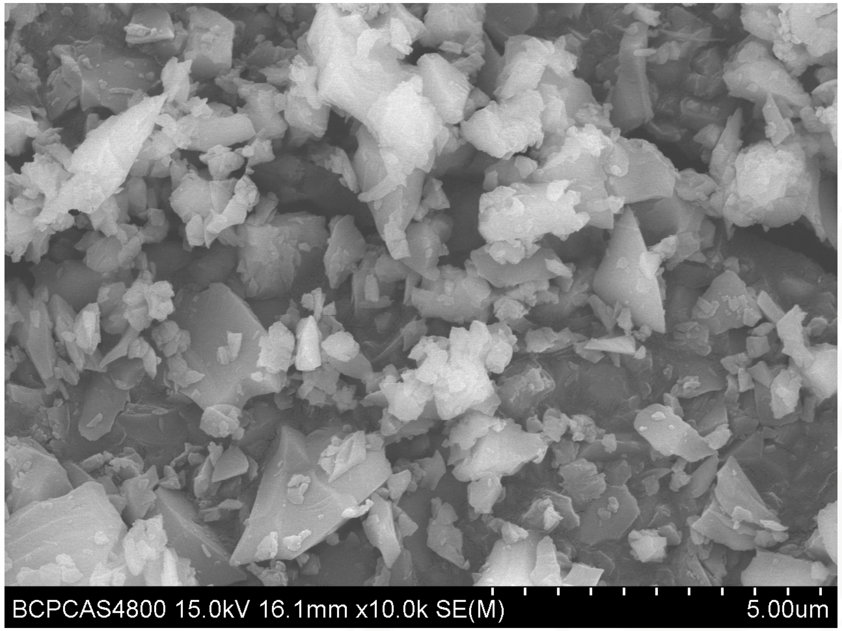
Experimetal test:

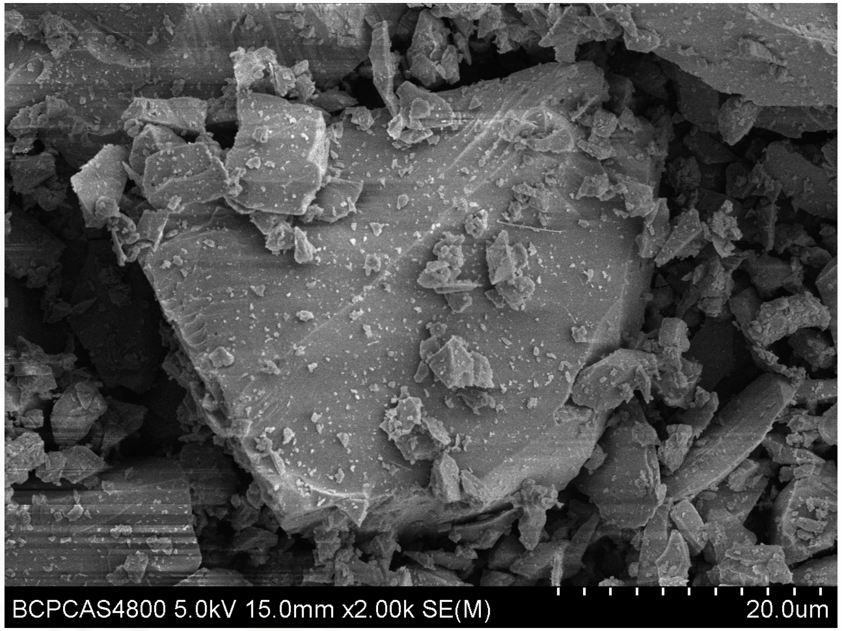
Materials

Porous medium (Quartz sands):

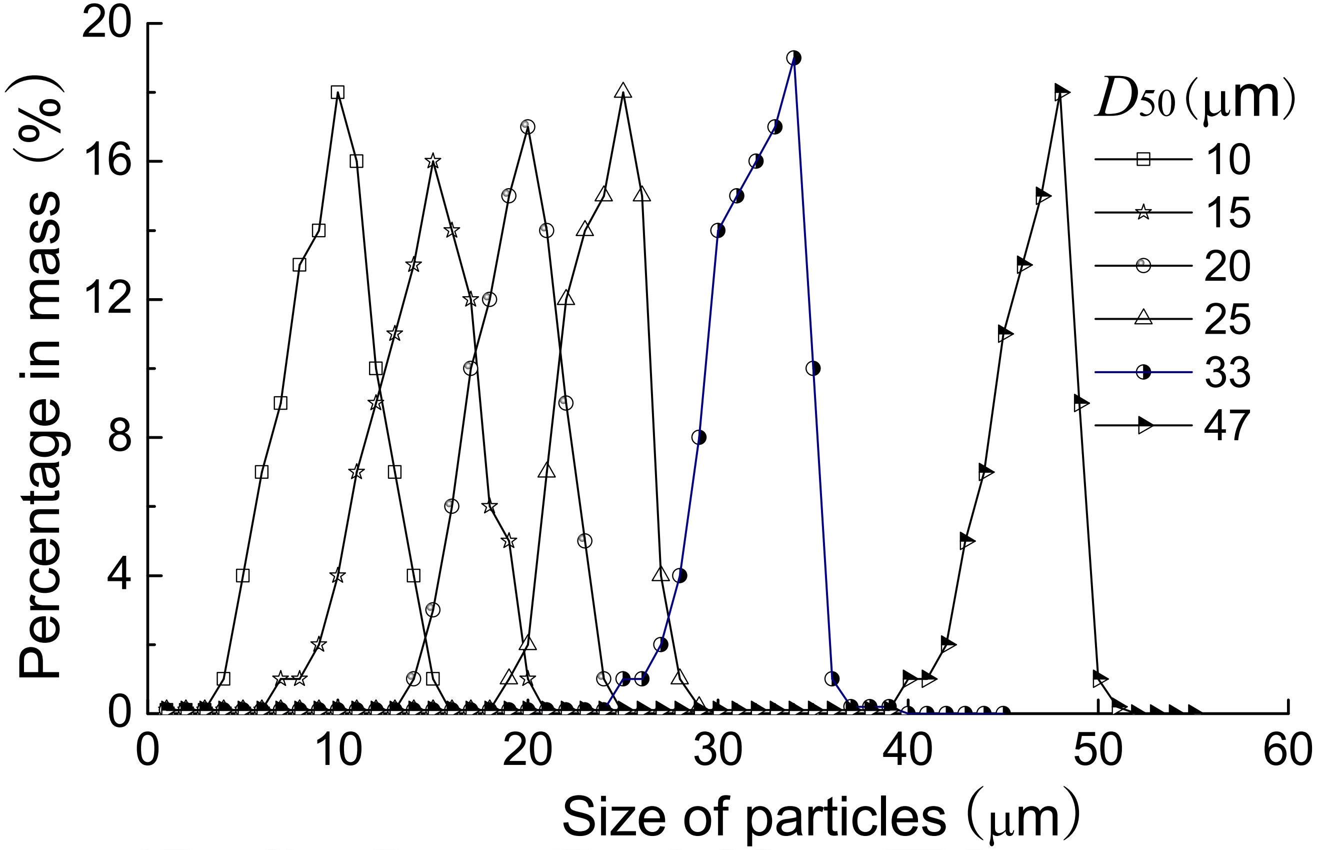
median diameter: d_g=1.18 mm; size range: 0.5–2 mm

SEM of SPs (D_{50}=10–47 μm):





Particle-size distribution of SPs



◆6 types, natural SiO_2 particles.

◆Unimodal particle size distribution.

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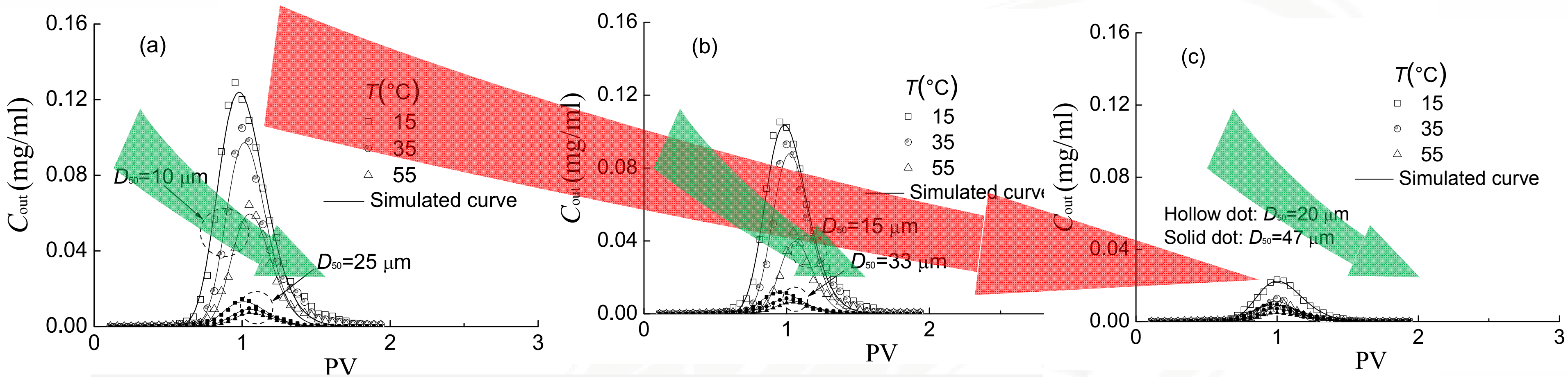
3 Test results

Effect of temperature(v=0.066 cm/s)

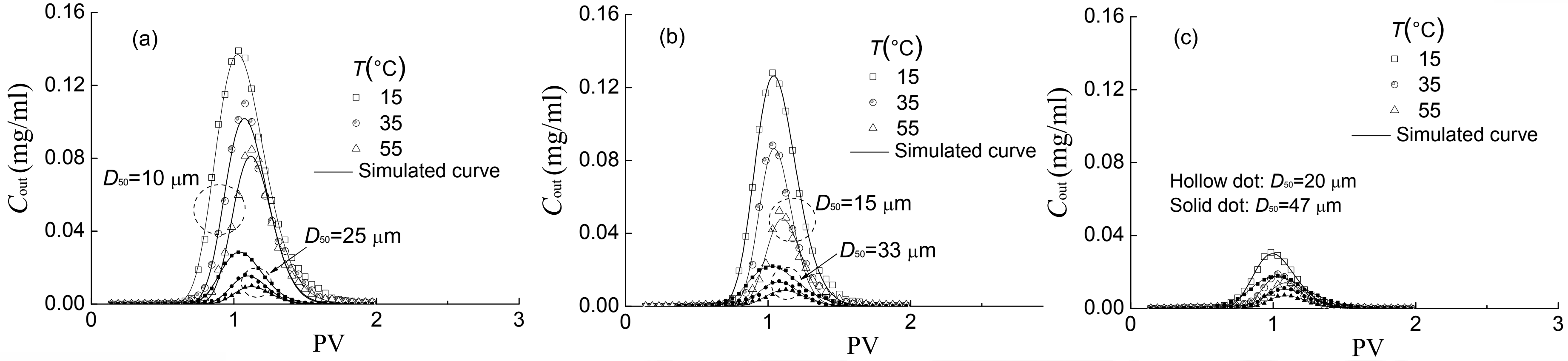


Breakthrough curves (BTCs):

C_{out} = particle concentration at the outlet $$PV = \frac{Q}{Vp}$$

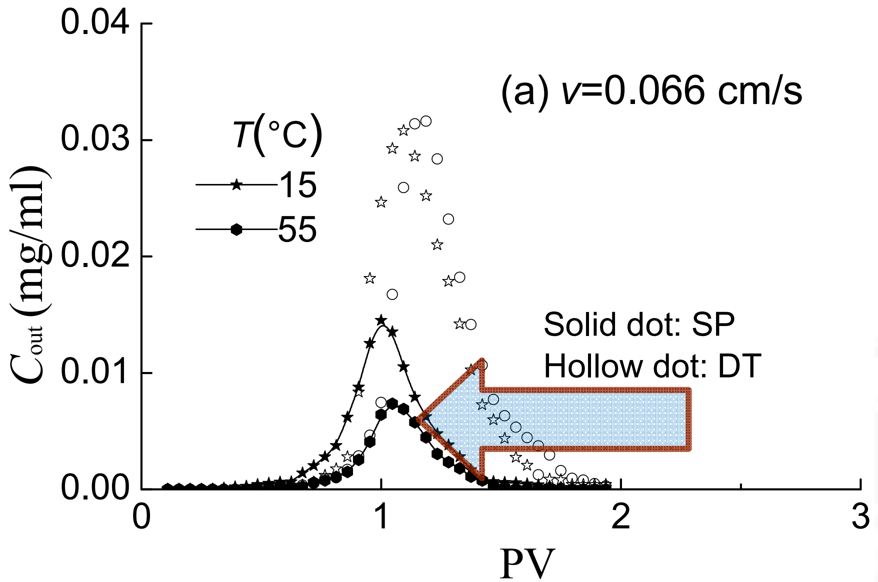
- Peak values decrease with increasing particles size.
- with increasing temperature.

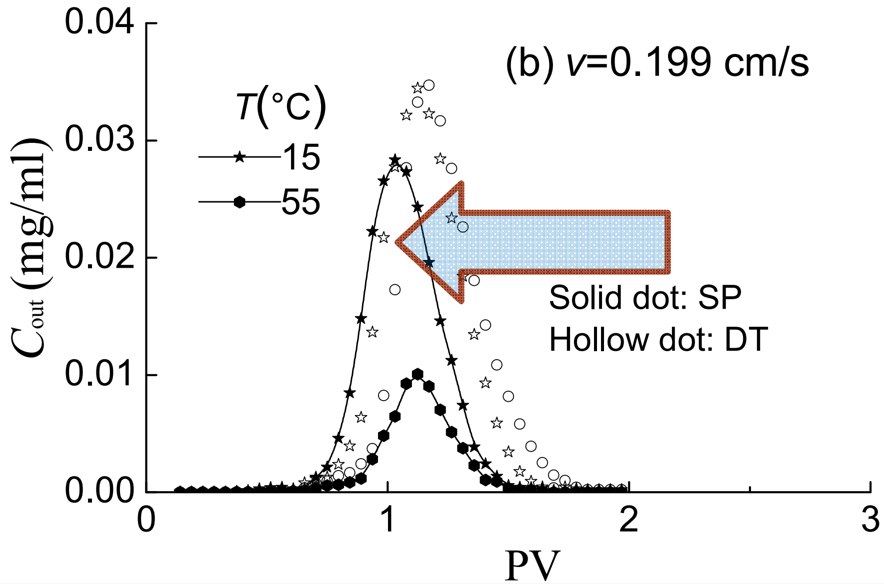
Effect of temperature (*v*=0.199 cm/s）



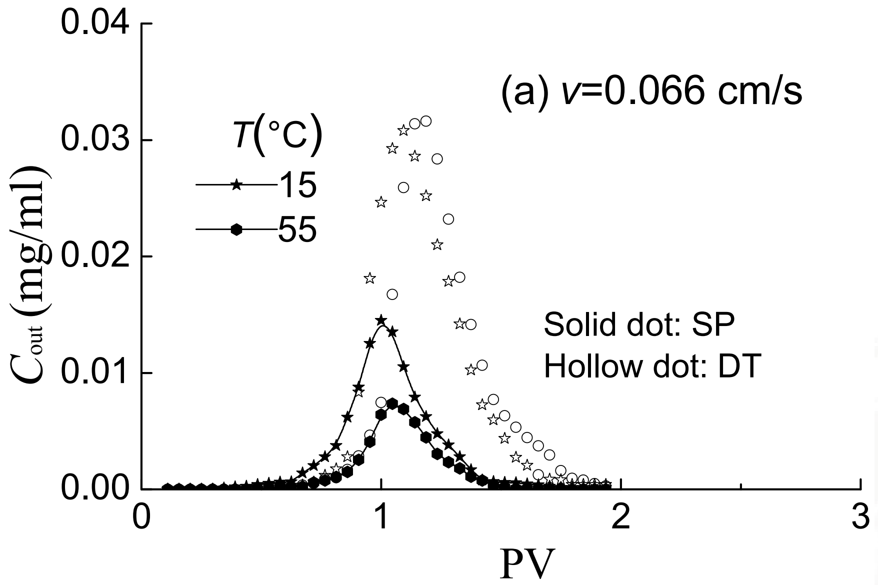
- The rise of temperature enhances the flow turbulence.
- The thermodynamic driving force increases with increasing temperature by the stochastic Brownian motion of SPs.
- The higher the temperature is, the higher the collision probability will be.
- Finally, straining deposition becomes more prominent.

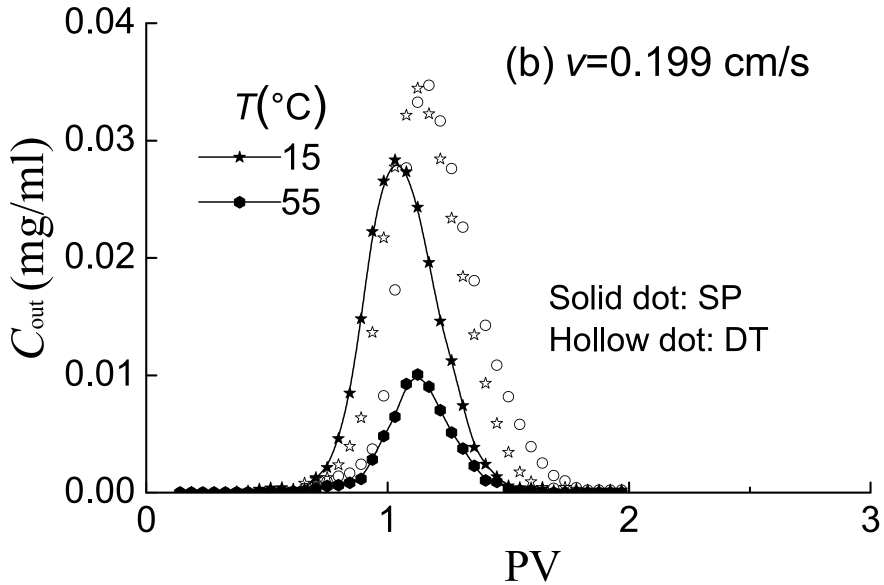
Comparison with conservative tracer





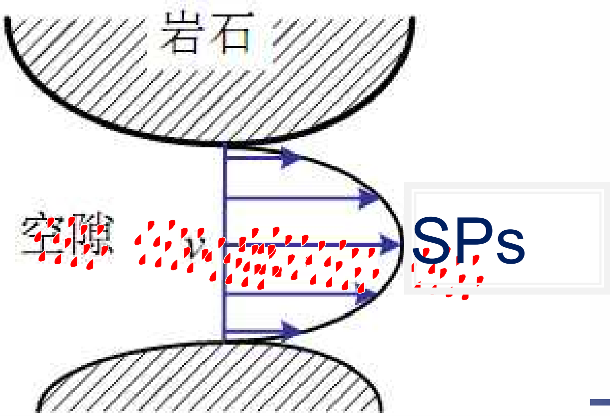
- DT: Dssolved tracer (conservative fluorescein).
- Migration velocity of SP is always faster than that of DT.
- This is due to the "size exclusion effect" of SPs.





Size exclusion effect:

- Large particles are only transported by higher velocities near the tube taxis.



4 Mathematical modeling

Highlight:

- *Based on convection-dispersion equation.*
- *Suitable for the case of long-time injection.*
- *For a variable concentration injection*
- *Accounting for the release effect of deposition.*

$$\frac{\partial C(z,t)}{\partial t} = D\frac{\partial^2 C(z,t)}{\partial z^2} - u\frac{\partial C(z,t)}{\partial z} - \frac{\rho_s}{n}\frac{\partial \sigma(z,t)}{\partial t}$$

where z is the coordinate, n is the porosity, D is hydrodynamic dispersion coefficient, u is the average interstitial particle velocity, t is time, σ is the concentration of the particles deposited onto the solid matrix, k_d is the deposition coefficient , and k_r is the release coefficient

$$\frac{\rho_s}{n}\frac{\partial \sigma(z,t)}{\partial t} = k_d \cdot C(z,t) - k_r \cdot \frac{\rho_s}{n}\sigma(z,t)$$

Deposition

Release

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By the Laplace transform and the Fourier transform (Bai et al., 2015):

$$C(z,t)=\exp(\frac{uz}{2D})\cdot\int_0^t g(\tau)\cdot[k_r\cdot W(z,t-\tau)+\frac{\partial W(z,t-\tau)}{\partial t}]d\tau$$

where:

$$W(z,t)=\exp^{-k_r t}\int_0^t I_0[2(\alpha\eta(t-\eta))^{1/2}]\cdot\frac{z}{2\eta\sqrt{\pi D\eta}}\cdot\exp[-\frac{z^2}{4D\eta}-\frac{u^2\eta}{4D}+(k_r-k_d)\eta]d\eta$$

$$\frac{\partial W(z,t)}{\partial t}=\exp^{-k_r t}\int_0^t\left\{(\frac{\alpha\eta}{t-\eta})^{1/2}I_1[2(\alpha\eta(t-\eta))^{1/2}]-k_r I_0[2(\alpha\eta(t-\eta))^{1/2}]\right\}$$

$$\cdot\frac{z}{2\eta\sqrt{\pi D\eta}}\cdot\exp[-\frac{z^2}{4D\eta}-\frac{u^2\eta}{4D}+(k_r-k_d)\eta]d\eta$$

$$+\ \exp^{-k_r t}\cdot\frac{z}{2t\sqrt{\pi Dt}}\cdot\exp[-\frac{z^2}{4Dt}-\frac{u^2 t}{4D}+(k_r-k_d)t]$$

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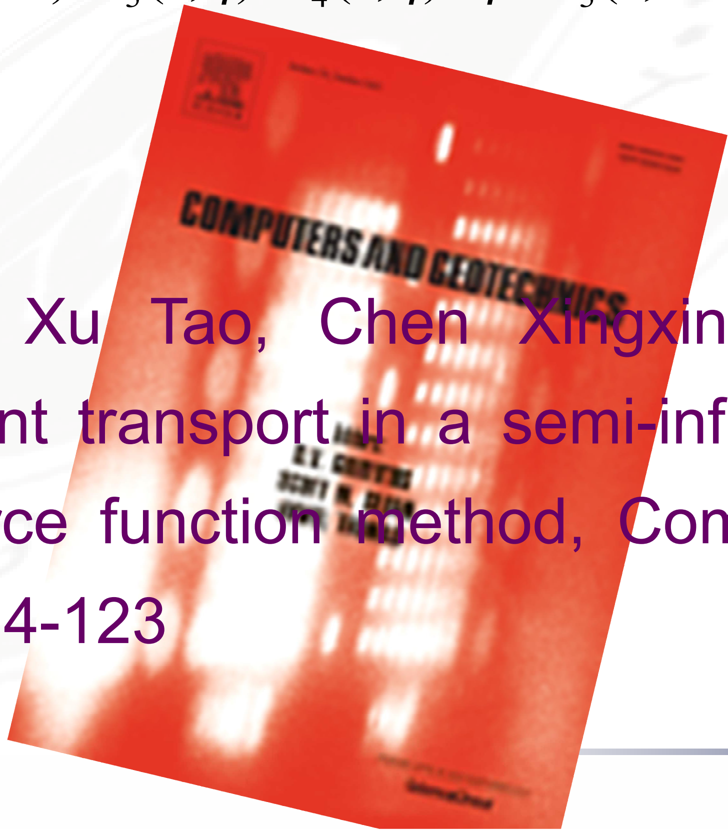
For an instantaneous plane source (Bai et al., 2015):

$$C_P(z,t-t') =$$

$$\frac{I}{2\sqrt{\pi D}} A_1(z,t-t') \left\{ \int_0^{t-t'} A_2(t-t') \cdot A_3(z,\eta) \cdot A_4(z,\eta) d\eta + A_3(z,t-t') \cdot A_4(z,t-t') \right\}$$

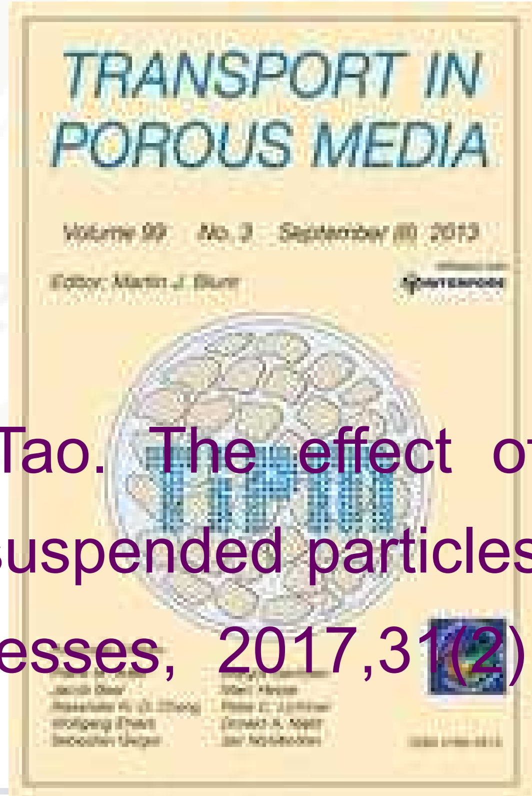


- Bai Bing, Li Huawei, Xu Tao, Chen Xingxin. Analytical solutions for contaminant transport in a semi-infinite porous medium using the source function method, Computers and Geotechnics,2015,69:114-123

For a *variable* sustained concentration

(Bai et al., 2015):

$$C(z,t)=\int_0^t C_{\mathrm{P}}(z,t-t')\cdot g(t')\cdot \mathrm{d}t'$$

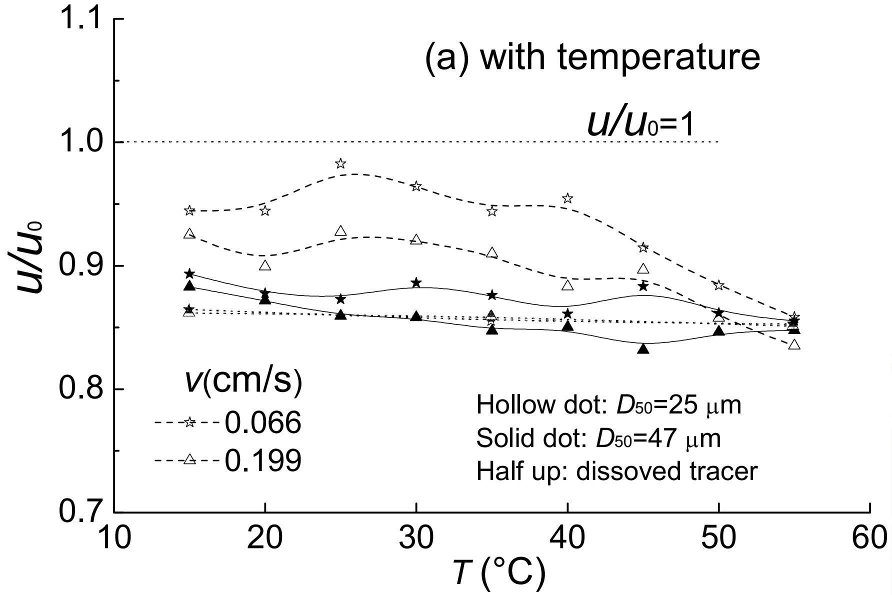


- Bai Bing, Long Fei, Rao Dengyu, Xu Tao. The effect of temperature on the seepage transport of suspended particles in a porous medium. Hydrological Processes, 2017,31(2): 382-393

5 Determination of transport parameters

- The theory provides a mathematical model to simulate the transport of SPs.
- Related to 4 parameters (particle velocity, dispersivity, deposition coefficient, release coefficient).
- Using Mathematica 9 (Wolfram Research).
- Breakthrough curves (BTCs) fit well with the experimental results (R^2>0.91).

Particle velocity



- The rise of temperature enhances the collisions between SPs and between SPs and matrix.
- Then, reduces the “size exclusion effect”.
- Finally, there is a negative correlation between u/u_0 and T .

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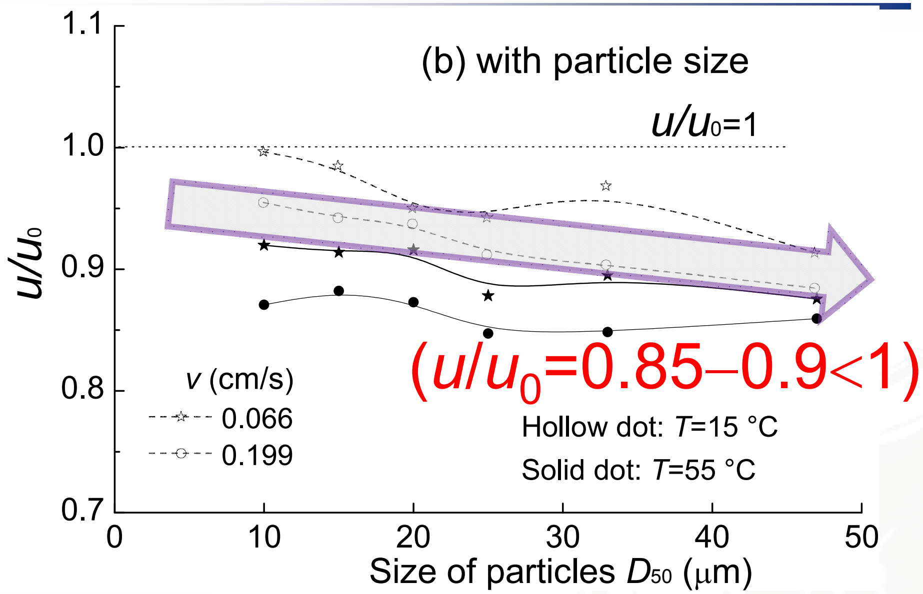
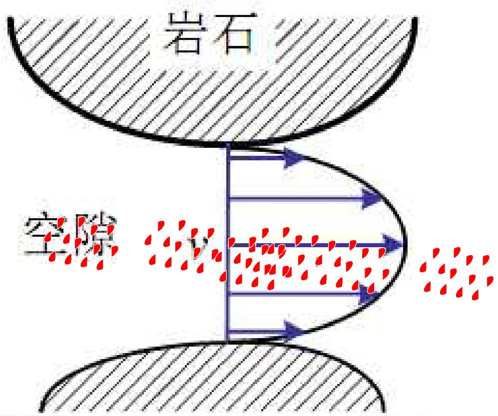
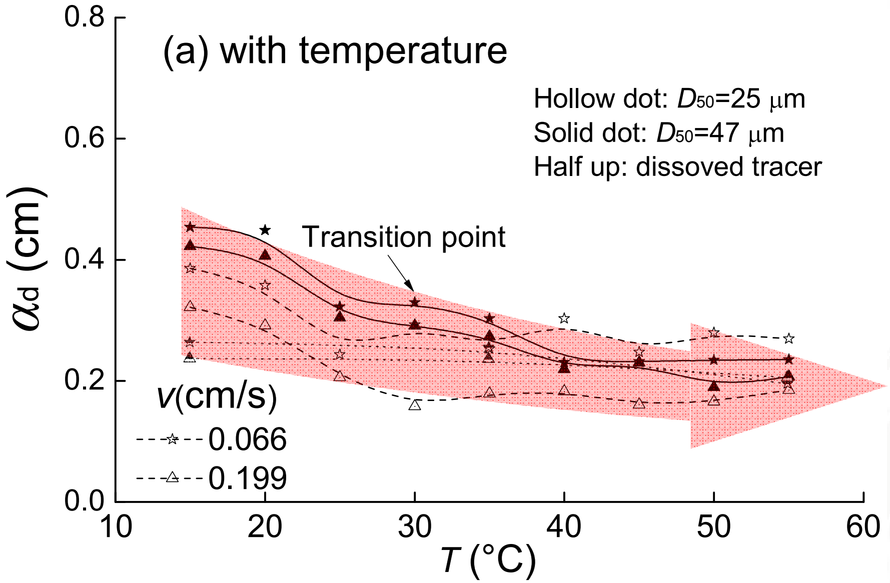




- Move velocity of SPs is smaller than the water velocity.
- And, decreases with increasing particle size.
- Different from the small-sized SPs ($u/u_0 > 1$)

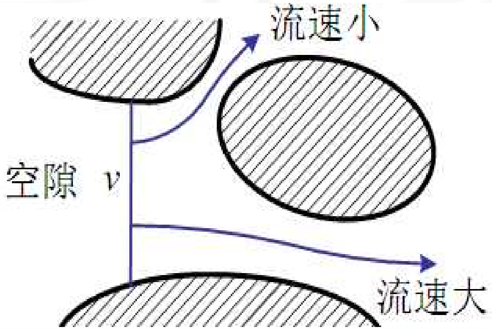
where the size exclusion effect seems to be more predominant.

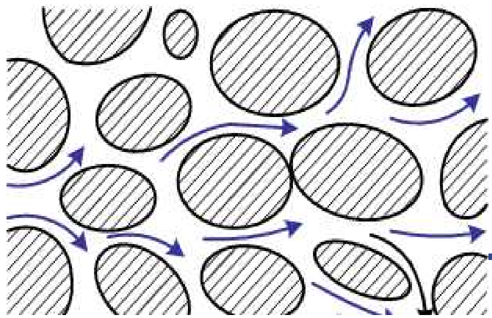
Dispersivity

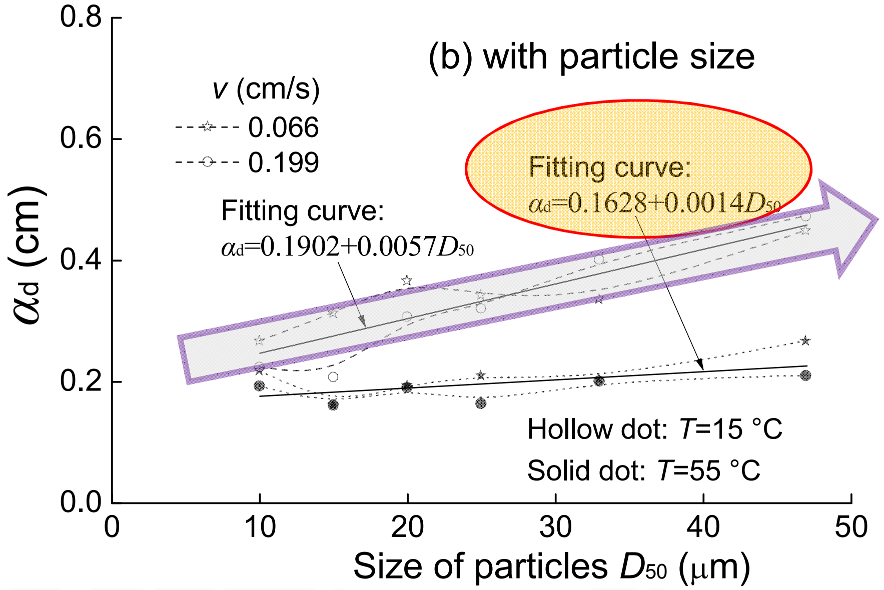


◆ Dispersivity decreases slightly at first with the increase of temperature to T=30 °C, and then remains almost constant.

Dispersivity:





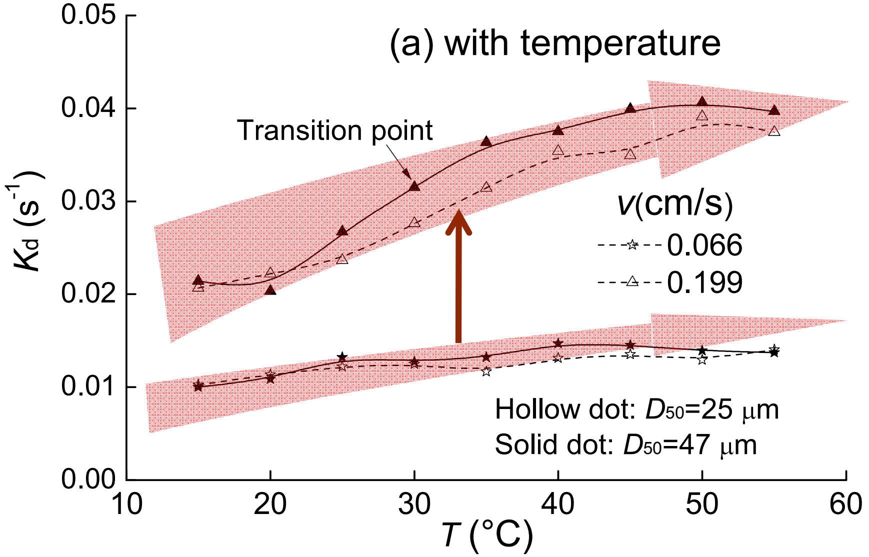


- Larger particles experience more irregular movements, and lead to a larger dispersivity.
- There is a positive correlation between α_d and D_{50}:

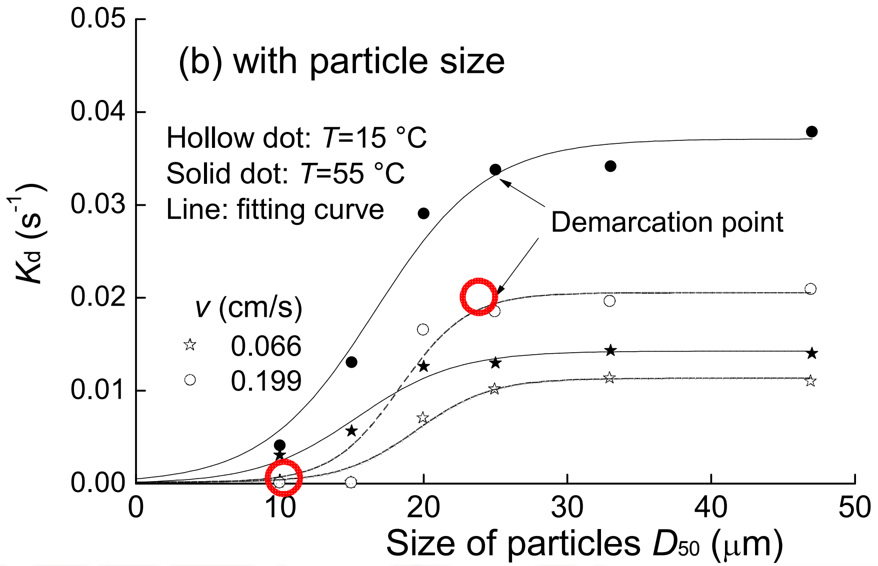
$$\alpha_d = d_1 + d_2 D_{50}$$

- At high temperature, the increase rate of dispersivity with particle size is much gentler than that at low temperatures.

Deposition coefficient

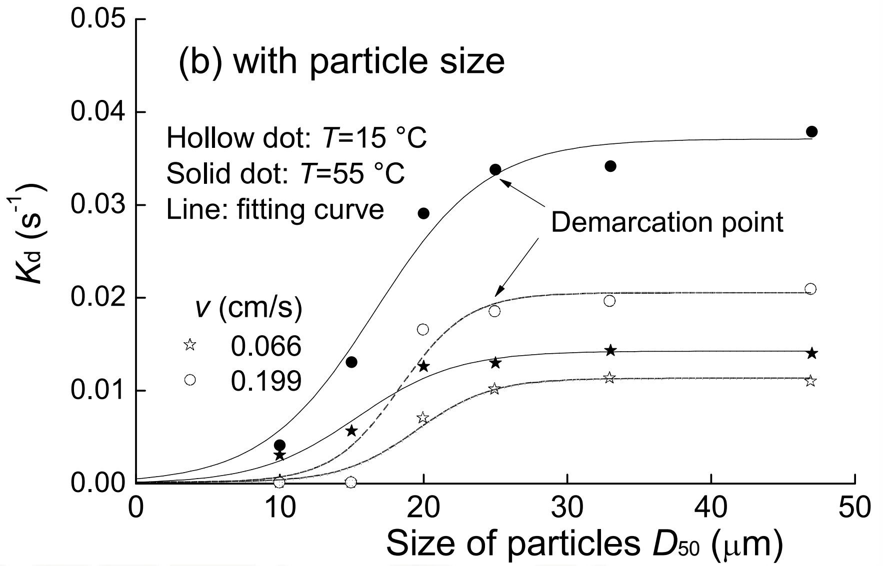


- The rise of temperature leads to the increase of deposition coefficient.
- Especially for a greater Darcy velocity (e.g., v=0.199 cm/s).



- k_d for large-sized particles are higher than small-sized.
- Be nearly zero when D_{50}< a threshold

  (e.g., when v=0.066 cm/s and T=15 °C, D_{50}=10 μm,D_{50}/d_g=0.008).
- When D_{50} > another critical value (e.g., D_{50}=25 μm), k_d remains largely unchanged.

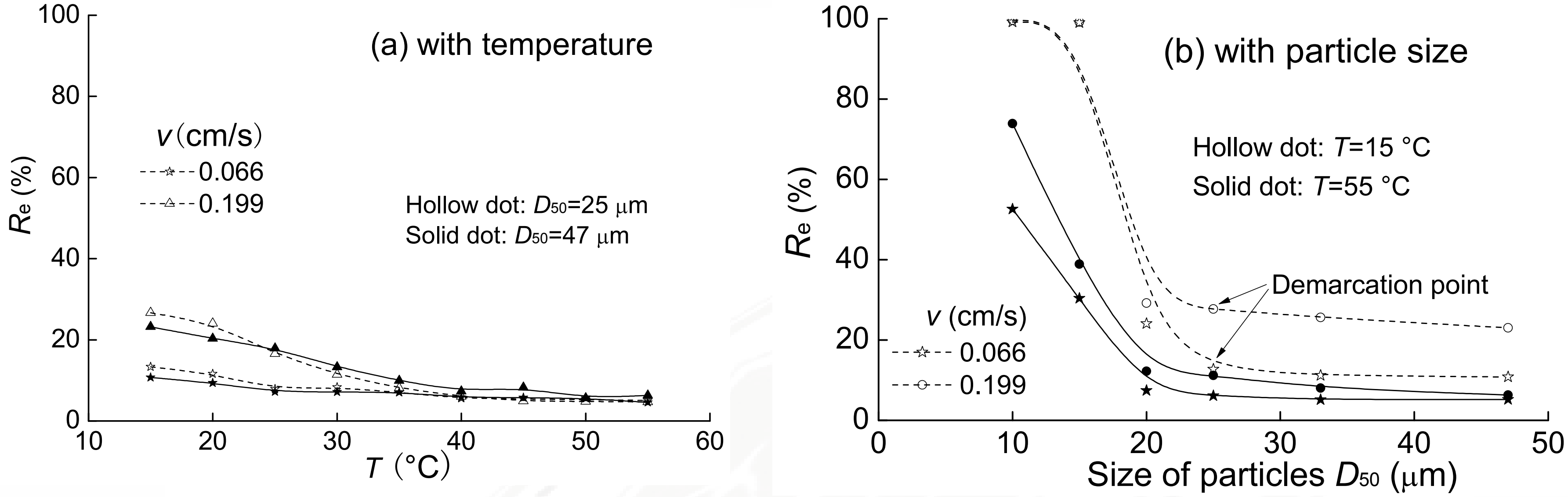


◆ A relationship between k_d and D_{50} can be expressed in the form of the Boltzmann function:

$$k_{\mathrm{d}} = k_{\mathrm{dmax}}\left[1 - \frac{1}{1+\exp^{(D_{50}/d_g - x_0)/\beta}}\right]$$

where k_{dmax} is the maximum value, x_0 is the center, and β is the shape parameter.

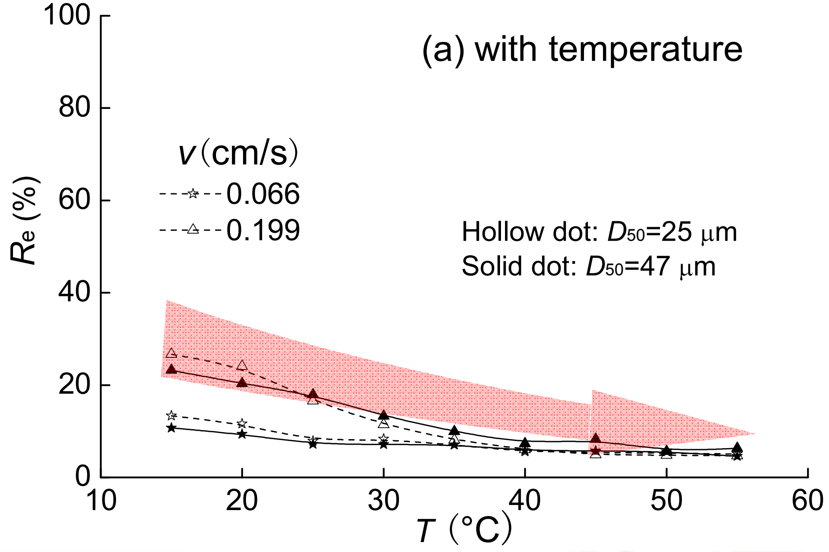
Recovery rate



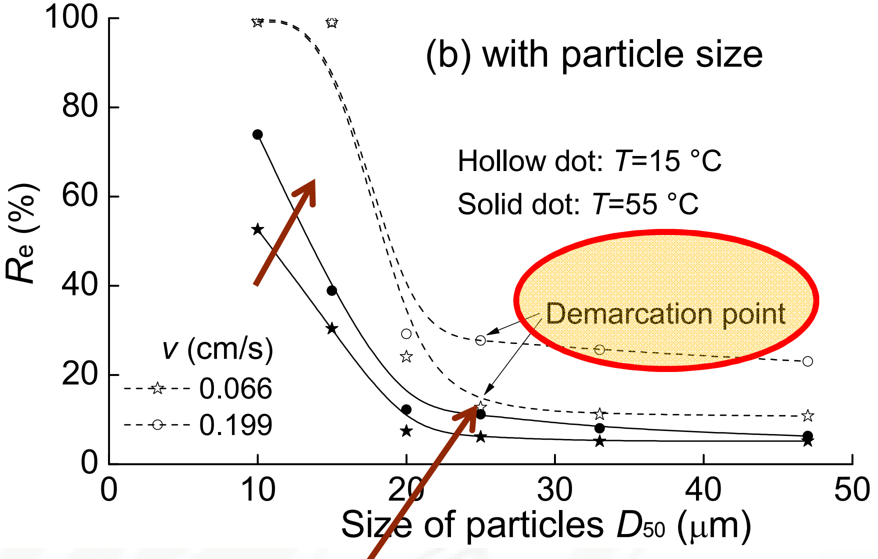
The recovery rate of SPs is defined as:

$$R_e = \int_0^\infty Q C_{out}(t) \mathrm{d}t / m$$

where R_e (%) is the ratio of SPs at the column outlet

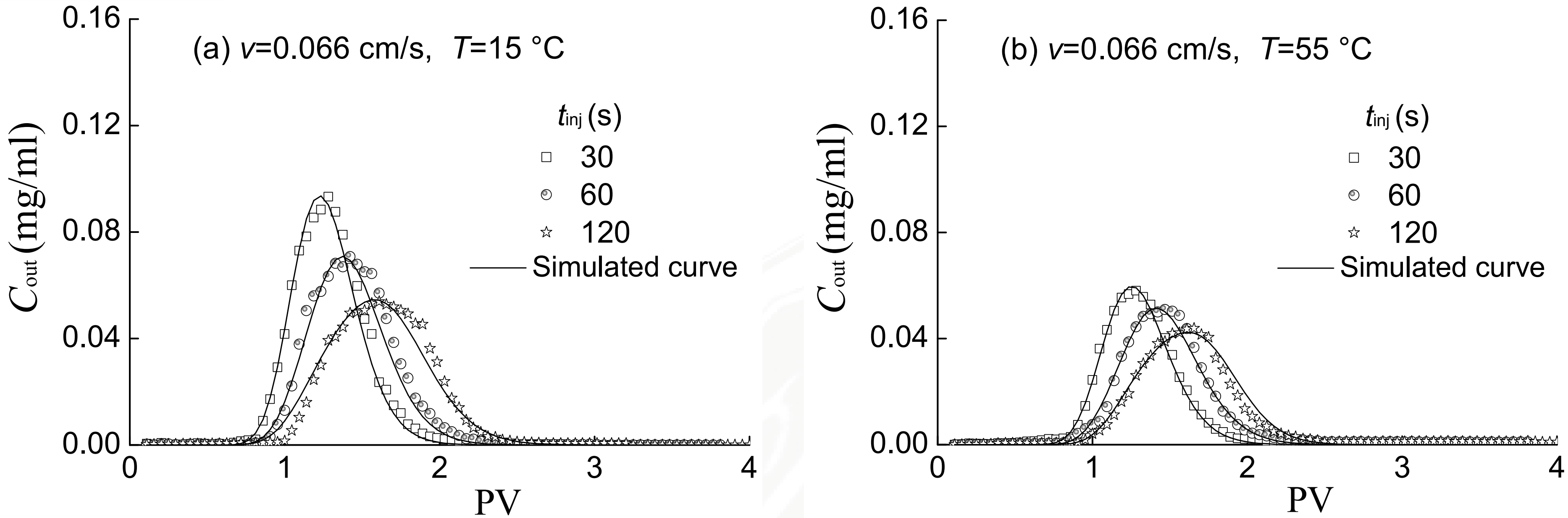


- Recovery rate decreases with increasing temperature.
- Indicating that the rise of temperature causes more repulsive interactions between SPs and between SPs and matrix.



- Recovery rate increases with the increase of flow velocity.
- Recovery rate decreases with increasing particle size until a demarcation point (i.e., D_{50}=25 μm).
- Be consistent with the threshold of the deposition coefficient.

6 Model verification:
sustained particle injection



- D_{50}=25 μm.
- Injected concentration: 3.75mg/ml.
- Injection duration: 30s, 60s, 120s.
- Two temperatures: T=15 °C and 55 °C.

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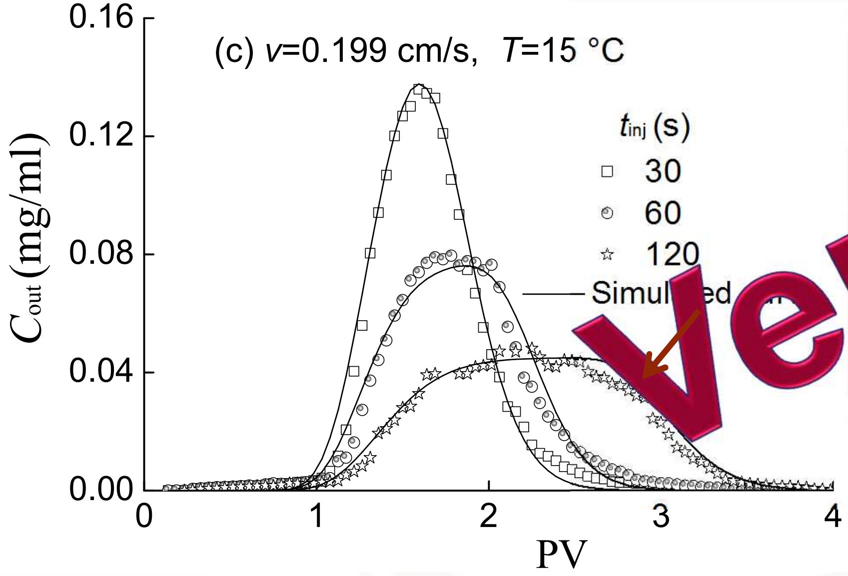
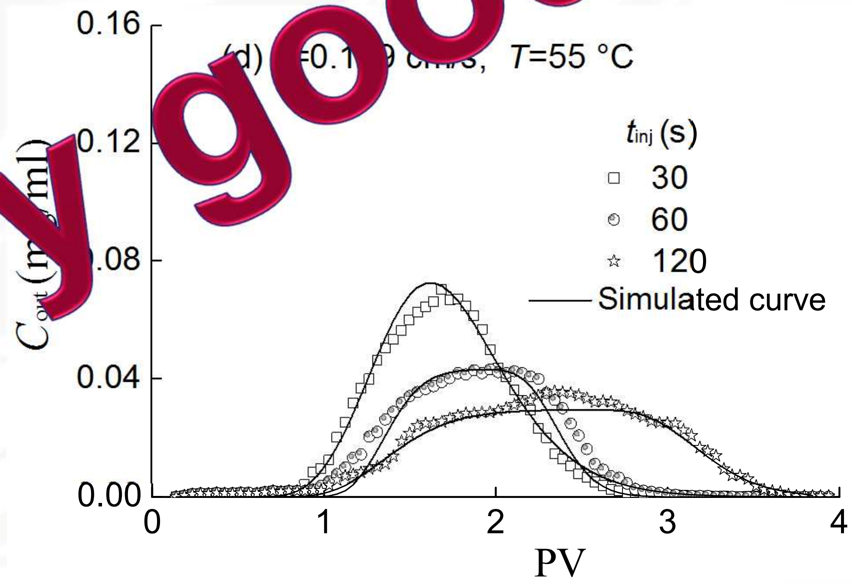
Fitting parameters

Temperature T (°C)	Darcy velocity v=0.066 cm/s			Darcy velocity v=0.199 cm/s		
	u/u_0	α_d (cm)	k_d (s^{-1})	u/u_0	α_d (cm)	k_d (s^{-1})
15	0.90	0.1	0.010	0.90	0.1	[illegible]
55	0.85	0.1	0.012	0.85	0.1	[illegible]

Very good!





Experimental data are well fitted with analytical solution (R^2>0.97)

THANKS