EGU General Assembly 2025

HOHAI UNIVERSITY

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Experimental and modeling assessment of slug tests in the presence of coupled hydraulic, thermal, and solute transport effects

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Sharing is encouraged

28 April 2025

Vienna, Austria

Curriculum Vitae

Xiaosong Dong

Education Background

Hohai University   Politecnico di Milano (CSC scholarship)

2022-Present: Doctoral degree (ongoing)   Ranking: Top 2/11

2020-2022: Master's degree   Ranking: Top 1/49

2016-2020: Bachelor's degree   Ranking: Top 5/77

Major: Geological Resource and Geological Engineering

Email: dongxiaosong@hhu.edu.cn

Research Achievements

✔**Publication:**

seven papers in English

ten papers in Chinese

✔**Patents:**

nine invention patents

✔**Research Projects:**

more than ten research projects

Selected Honors & Awards

✔National Scholarship (Top 1%)

✔Outstanding Student Leader (Top 1%)

✔Outstanding Graduates (Top 5%)

✔Outstanding Presenter/Student (Top 10%)

✔Academic Excellence Scholarship (Top 10%)

✔Sci&Tech Innovation Scholarship (Top 10%)

✔First class Postgraduate Scholarship (Top 30%)

Internship & Activities

✔ Student Membership of CSRME

✔ Alumni Liaison Staff of Hohai University

✔ Vice President of Graduate Student Association

✔ Secretary General of the Student Self-Management Committee

CONTENT

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01 Research Background

1. Research Background

hydrogeological parameters

Multi-field coupling

slug tracer test

①There are still many problems in the comprehensive determination of hydrogeological parameters in aquifers;

②Slug test is known for its small impact area and easy operation;

③Tracer test is used to determine the dispersion coefficient of an aquifer;

④Multi-field coupling is an extremely complex problem

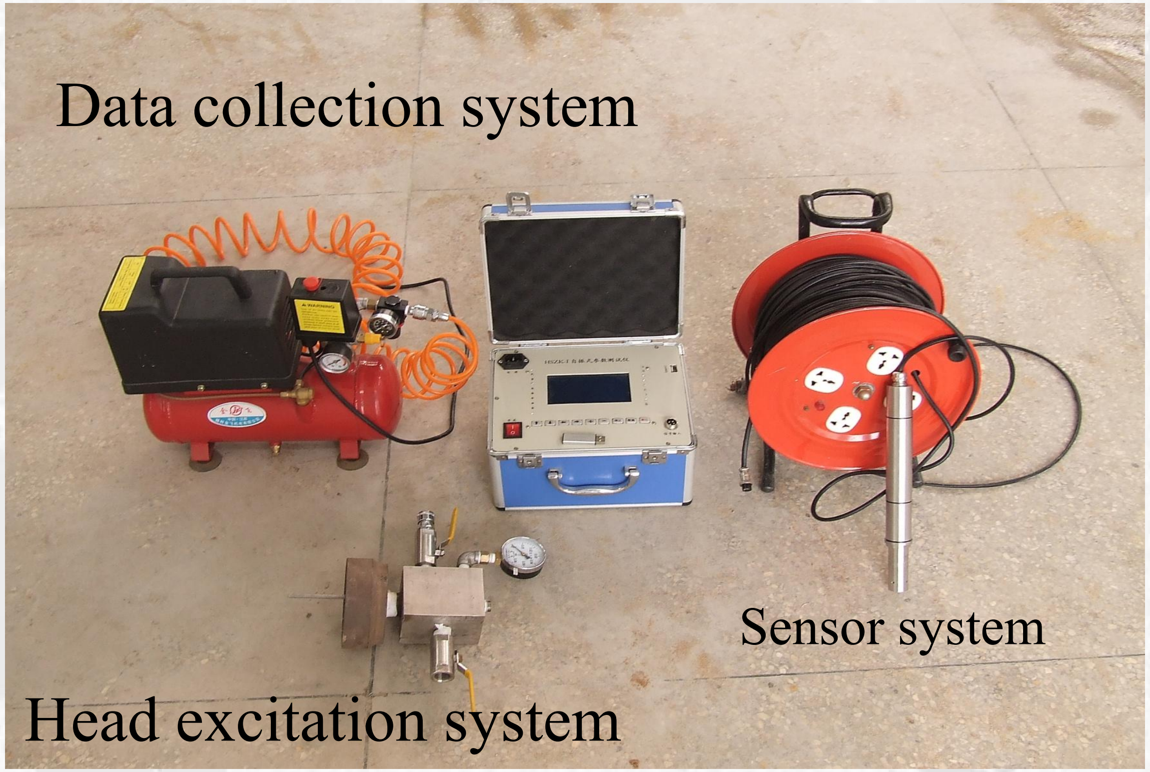
1. Research Background

Slug Test

(1) Slug tests use a single well for the determination of aquifer

(2) Rather than pumping the well for a period of time, a volume of water is suddenly removed or added to the well casing and observations of recovery or drawdown are noted through time

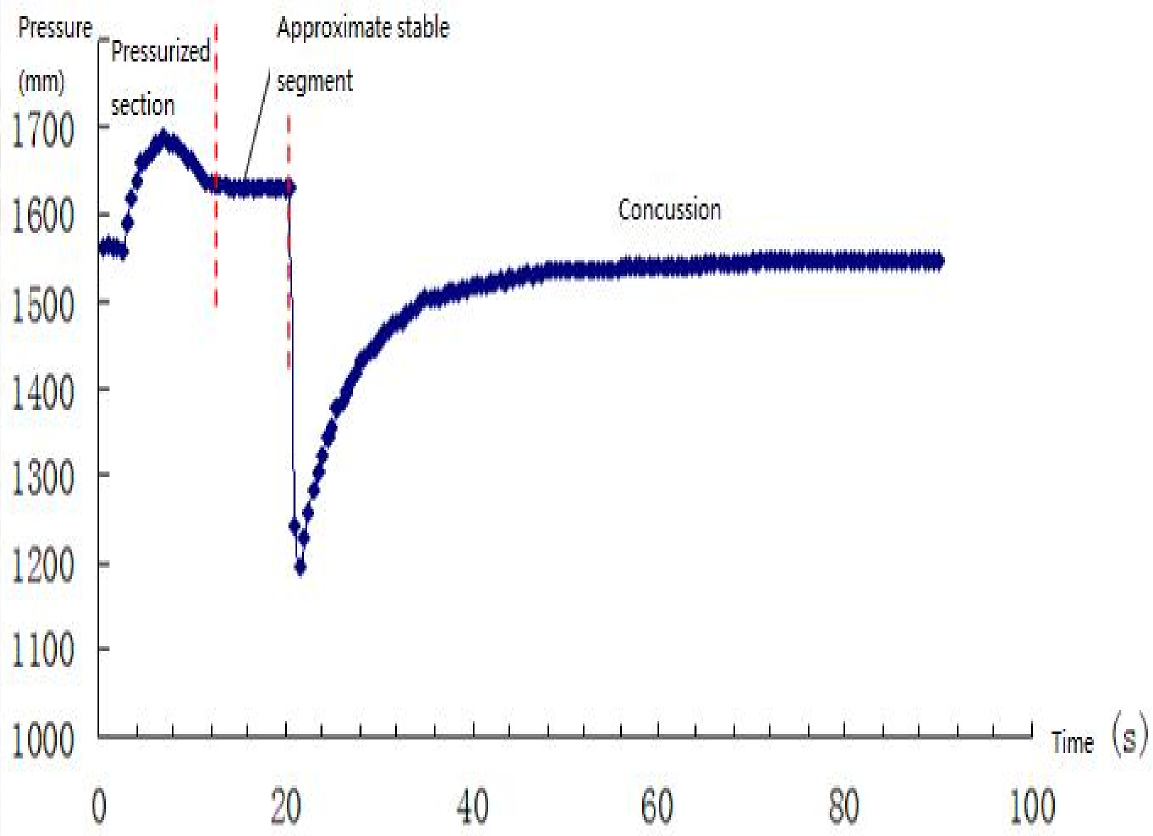
(3) Slug tests are often preferred at hazardous waste sites, since no contaminated water has to be pumped out and then disposed.

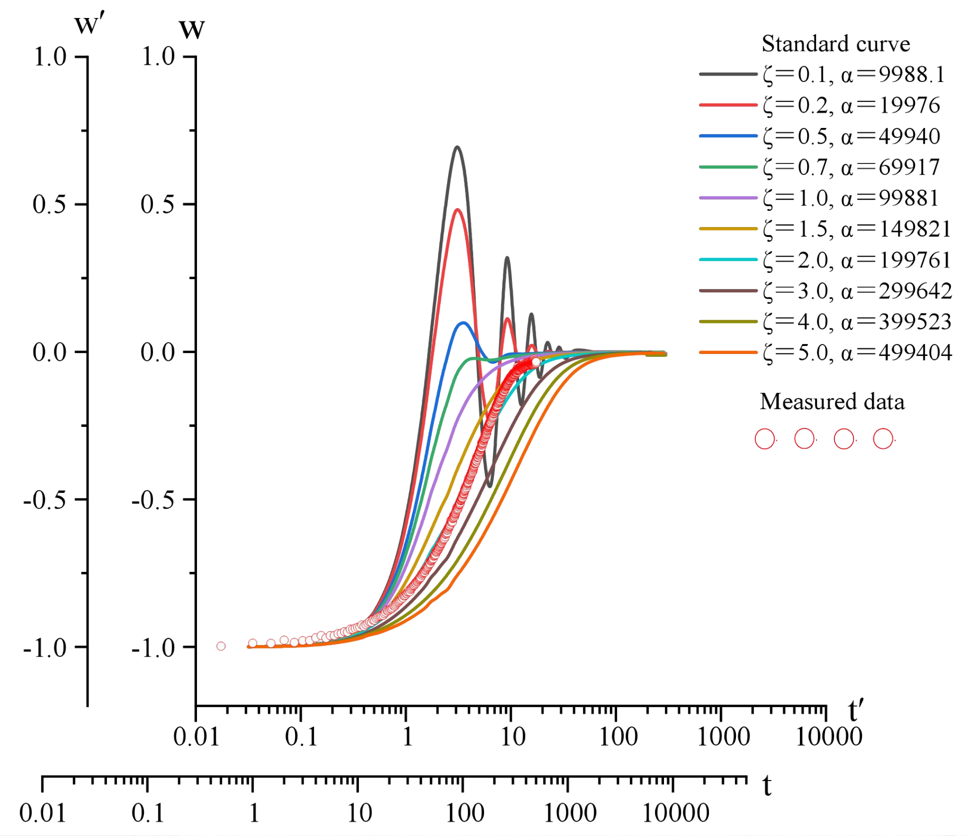


Pictures of the slug test system

1. Research Background

Slug Test

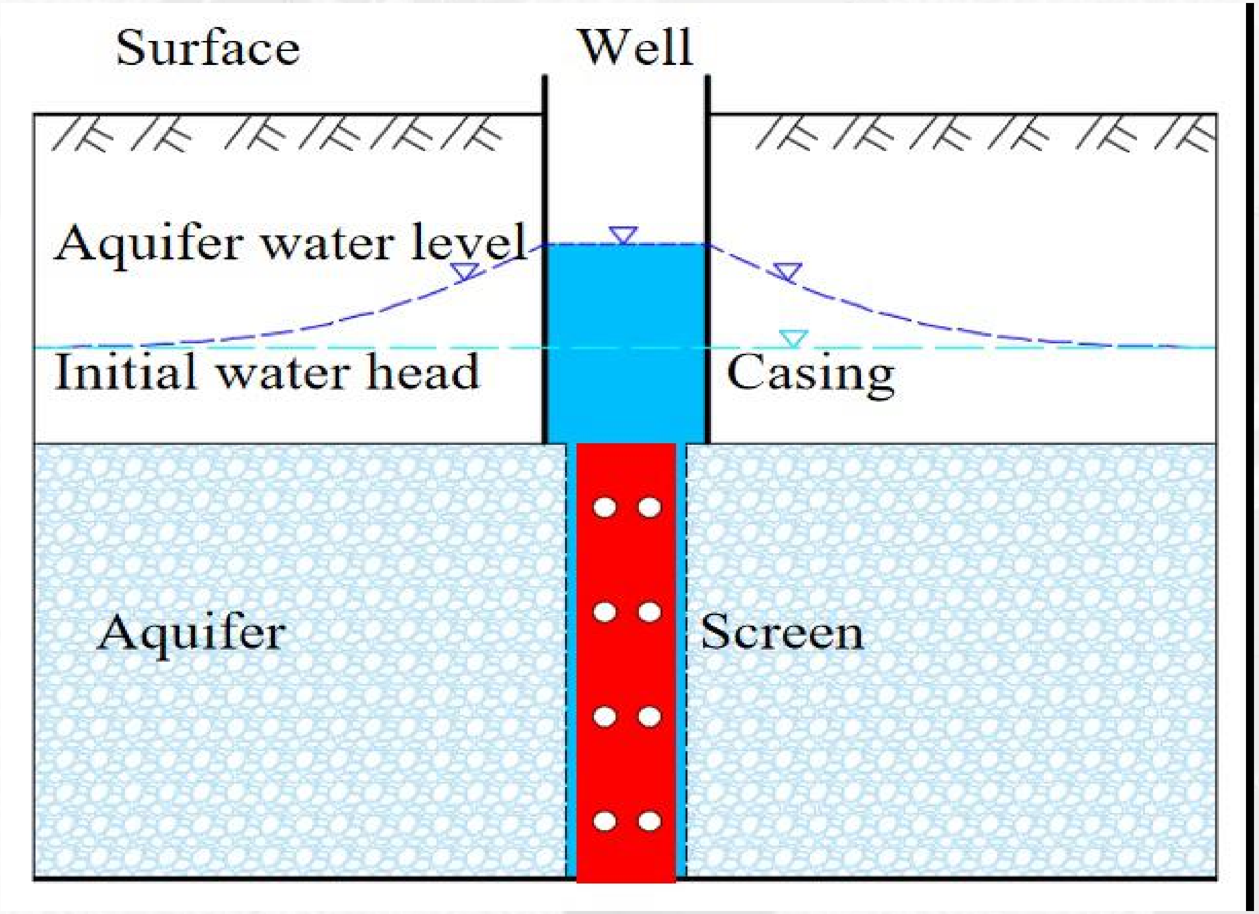




Measured curve & standard curve of slug test

1. Research Background

slug heat test



Experience model studies

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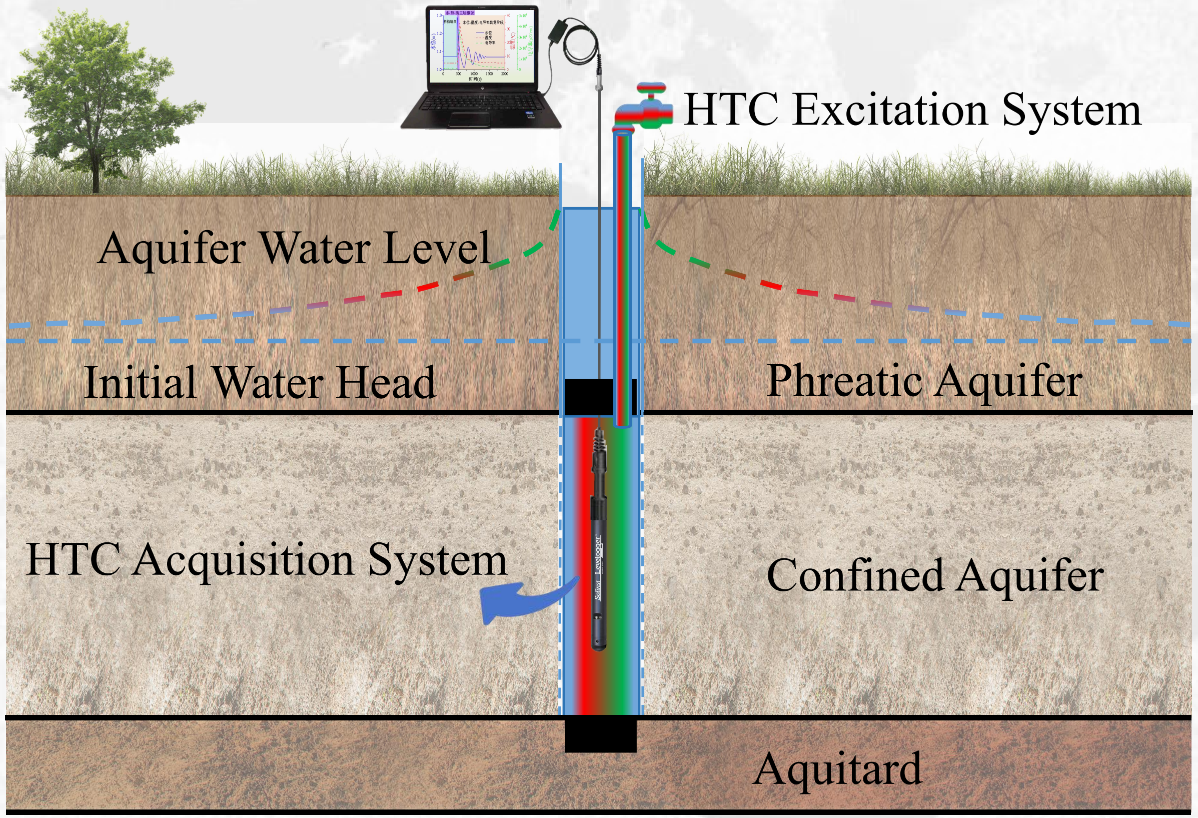
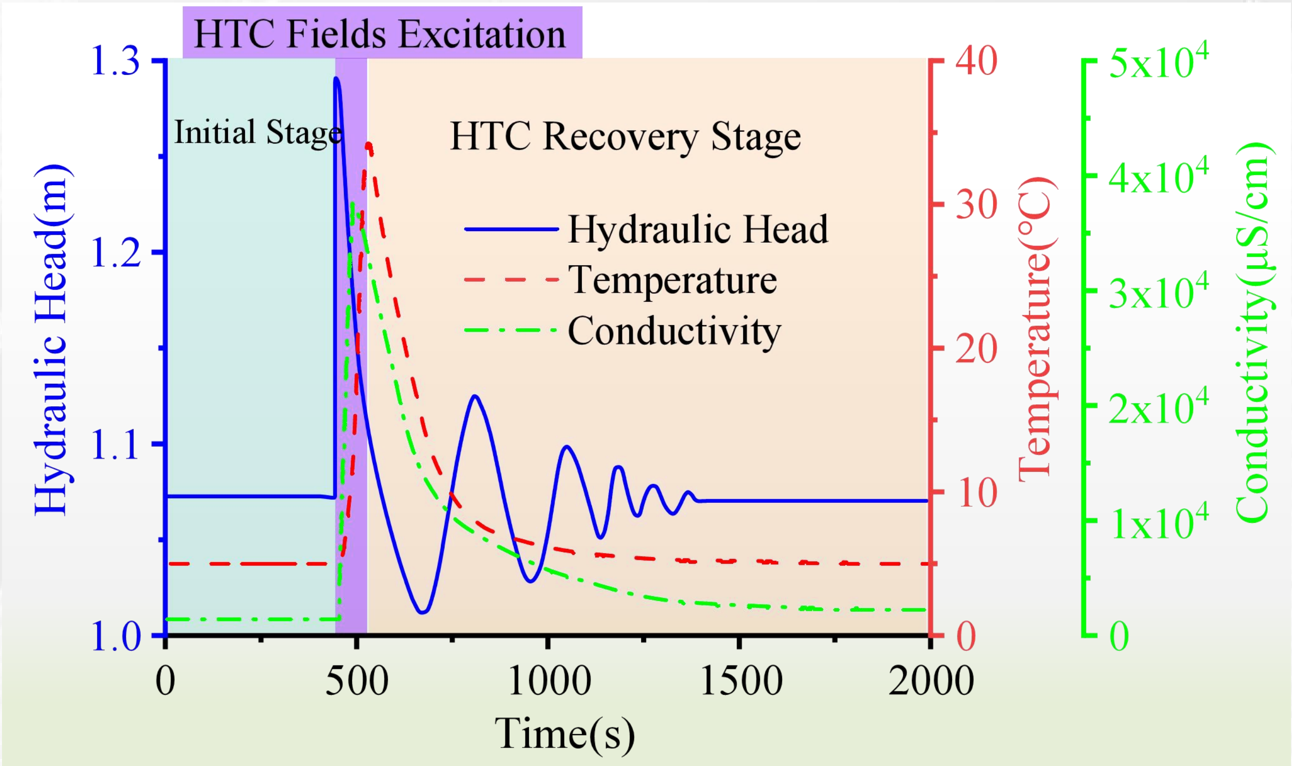
02 Laboratory Model

2. Laboratory Model

Hydraulic-Thermal-Chemical Fields Coupling



Experimental Schematic Diagram



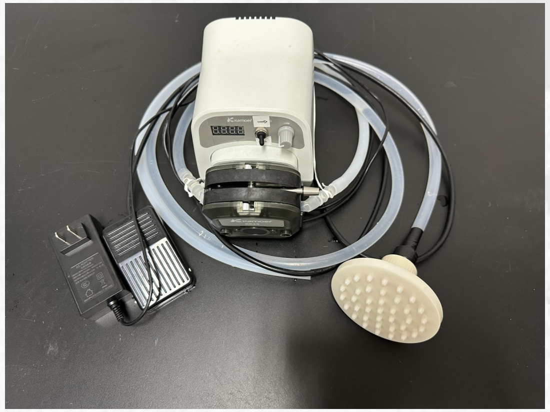
Schematic Diagram of Experimental Data

2. Laboratory Model

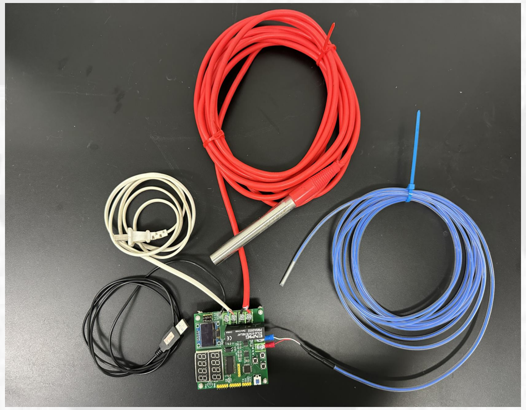
HTC Probe

Data Transmitter

Data Cable



Peristaltic Pump



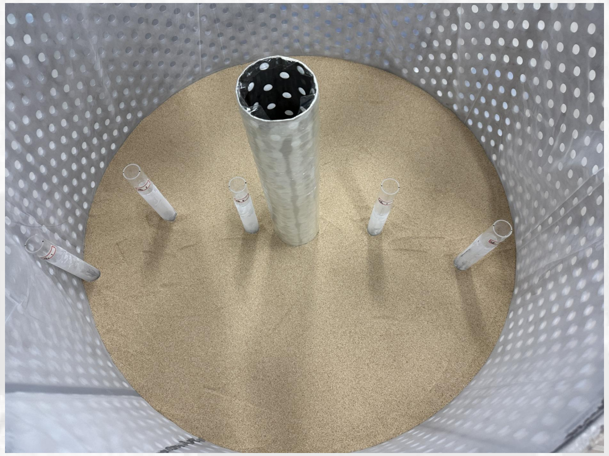
Heating Rod

Digital Screen

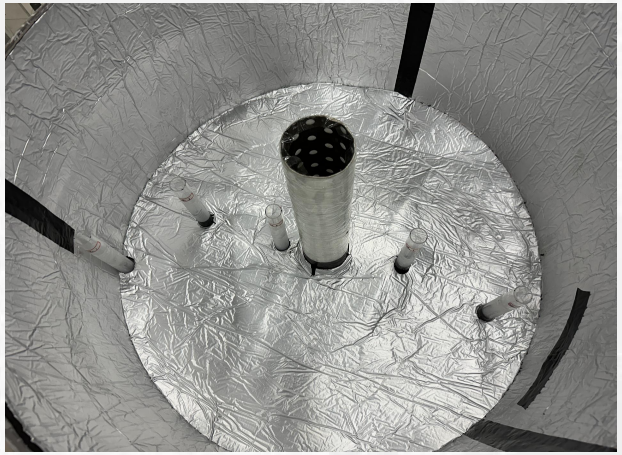
Overall Diagram of Platform

One-dimensional Experimental Platform

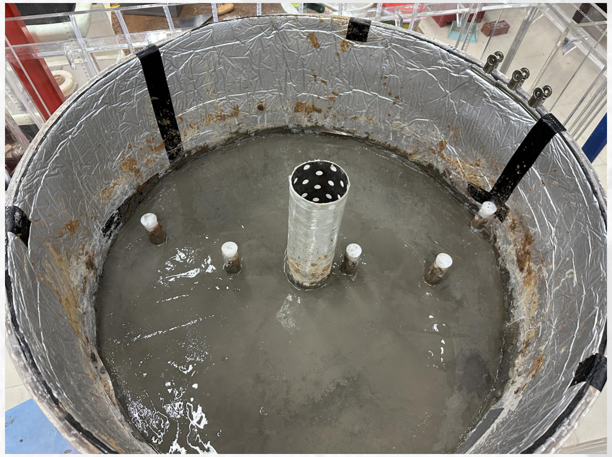
2. Laboratory Model



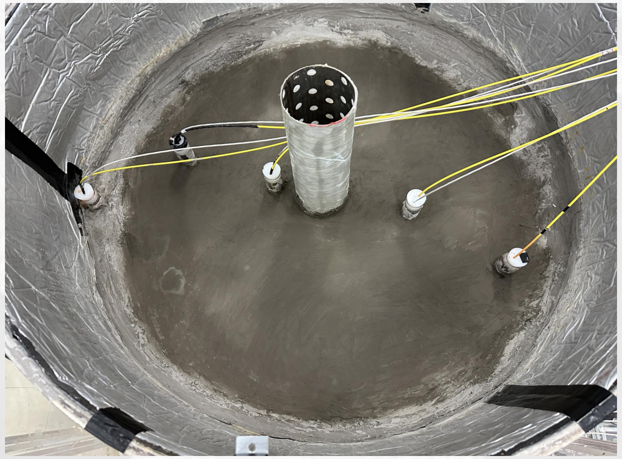
Sand Filling



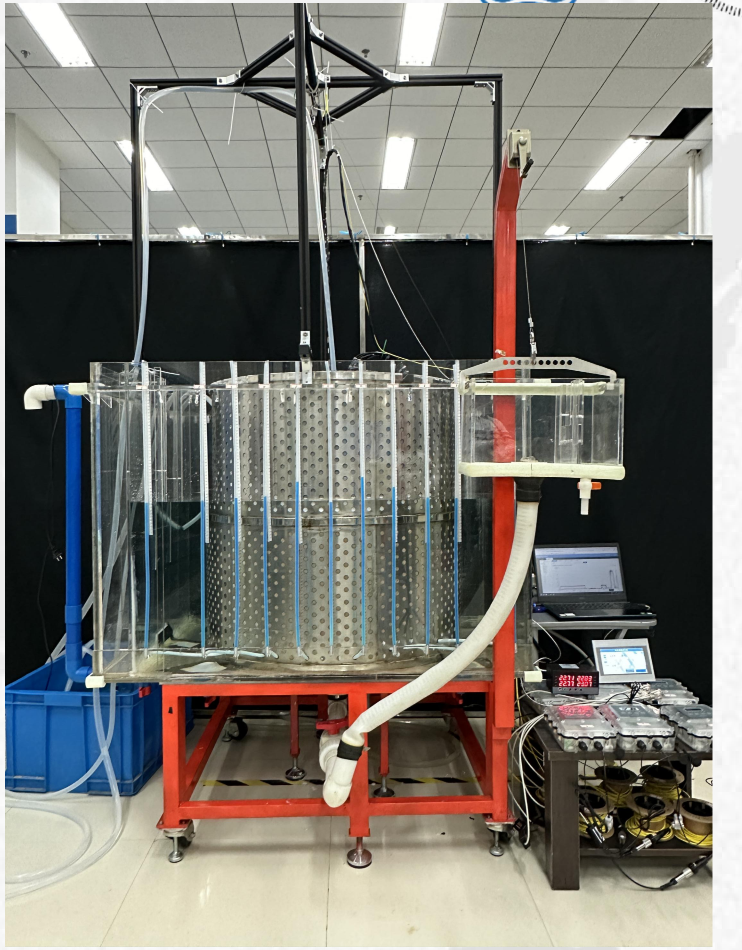
Heat Protection Film



Cement Filling



Top View



Front View

Two-dimensional Experimental Platform

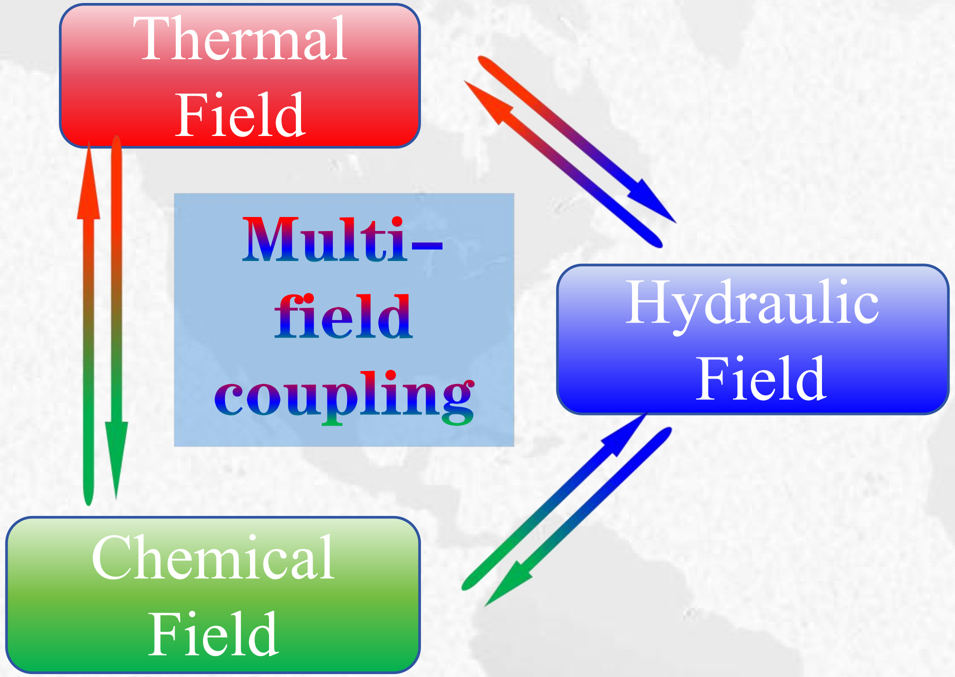
03 Theory and Methods

3. Theory and Methods

$$c\rho\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left(\lambda_x\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\lambda_y\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\lambda_z\frac{\partial T}{\partial z}\right)-\frac{\partial}{\partial x}\left(c_w\rho_w T\cdot u_x\right)-\frac{\partial}{\partial y}\left(c_w\rho_w T\cdot u_y\right)-\frac{\partial}{\partial z}\left(c_w\rho_w T\cdot u_z\right)+f$$

Thermal Transport Equation : ↑↑↑

Heat Balance Equation : $(\rho c)_w \pi r_c^2 \frac{d(hT_*)}{dt} = 2\pi r_s \cdot \lambda M \left.\frac{dT}{dr}\right|_{r=r_s}$



Groundwater Continuity Equation :

$$\mu_s\frac{\partial H}{\partial t}=\frac{\partial}{\partial x}(K_x\frac{\partial H}{\partial x})+\frac{\partial}{\partial y}(K_y\frac{\partial H}{\partial y})+\frac{\partial}{\partial z}(K_z\frac{\partial H}{\partial z})$$

Water Balance Equation : $\pi r_c^2 \frac{dw}{dt} = 2\pi r_s \cdot T \left.\frac{\partial h}{\partial r}\right|_{r=r_s}$

Solute Transport Equation : ↓↓↓

Solute Balance Equation : $\pi r_c^2 \frac{d(hC_*)}{dt} = 2\pi r_s \cdot DM \left.\frac{dC}{dr}\right|_{r=r_s}$

$$\frac{\partial C}{\partial t}=\frac{\partial}{\partial x}\left(D_x\frac{\partial C}{\partial x}\right)+\frac{\partial}{\partial y}\left(D_y\frac{\partial C}{\partial y}\right)+\frac{\partial}{\partial z}\left(D_z\frac{\partial C}{\partial z}\right)-\frac{\partial}{\partial x}\left(C\cdot u_x\right)-\frac{\partial}{\partial y}\left(C\cdot u_y\right)-\frac{\partial}{\partial z}\left(C\cdot u_z\right)+I$$

3. Theory and Methods

Multi-field coupling

1.Hydraulic field

K: Hydraulic Conductivity

μ_s: Storage Coefficient

v: Darcy’ s velocity

2.Thermal field

λ: Thermal Conductivity

ρ : Density

c: Heat Capacity

α_h: Thermal dispersivity

3.Chemical field

D_L: Dispersion Coefficient

D_0: *Molecular Diffusion Coefficient*

α_L: Dispersivity

3. Theory and Methods

	One-dimensional sand column model	two-dimensional well flow model
Hydraulic Field	$\mu_s\frac{\partial H}{\partial t}=K\frac{\partial H}{\partial x^2}$ $H(x,0)=H_0$ $H(L,t)=H_0$ $H(0,t)=H_w(t)+H_0$ $\frac{dH_w}{dt}=K\frac{\partial H}{\partial x}\Big\vert_{x=0}$ $H_w(0)=H_{w0}$ $v(x,t)=-K\frac{\partial H}{\partial x}$	$\mu_s\frac{\partial H}{\partial t}=\frac{1}{r}\frac{\partial}{\partial x}\left(Kr\frac{\partial H}{\partial r}\right)$ $H(r,0)=H_0$ $H(L,t)=H_0$ $H(0,t)=H_w(t)+H_0$ $\frac{dH_w}{dt}=\frac{2bK}{r_w}\frac{\partial H}{\partial r}\Big\vert_{r=0}$ $H_w(0)=H_{w0}$ $v(r,t)=-K\frac{\partial H}{\partial r}$
Chemical Field	$\frac{\partial(nC)}{\partial t}=\frac{\partial}{\partial x}\left(nD_x\frac{\partial C}{\partial x}-vC\right)$ $D_x=D_0+\alpha_{cx}\cdot\frac{v}{n}$ $C(x,0)=C_0$ $C(L,t)=C_0$ $C(0,t)=C_w(t)+C_0$ $\frac{d\left[(H_w+H_0)(C_w+C_0)\right]}{dt}=\left(nD_x\frac{\partial C}{\partial x}-vC\right)\Big\vert_{x=0}$ $C_w(0)=C_{wo}$	$\frac{\partial(nC)}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left(nD_r r\frac{\partial C}{\partial r}\right)-\frac{1}{r}\frac{\partial(vrC)}{\partial r}$ $D_r=D_0+\alpha_{cr}\cdot\frac{v}{n}$ $C(r,0)=C_0$ $C(L,t)=C_0$ $C(0,t)=C_w(t)+C_0$ $\frac{d\left[(H_w+H_0)(C_w+C_0)\right]}{dt}=\frac{2b}{r_w}\left(nD_r\frac{\partial C}{\partial r}-vC\right)\Big\vert_{x=0}$ $C_w(0)=C_{wo}$
Thermal Field	$(\rho c)_f\frac{\partial T}{\partial t}=\frac{\partial}{\partial x}\left[\lambda_x\frac{\partial T}{\partial x}-(\rho c)_f vT\right]$ $\lambda_x=\lambda_p+\lambda_{vx}$ $\lambda_p=(\rho c)_{fs}\left[n\frac{\lambda_f}{(\rho c)_f}+(1-n)\frac{\lambda_s}{(\rho c)_s}\right]$ $\lambda_p=n\lambda_f+(1-n)\lambda_s$ $\lambda_{vx}=\alpha_{hx}(\rho c)_f v$ $T(x,0)=T_0$ $T(L,t)=T_0$ $T(0,t)=T_w(t)+T_0$ $(\rho c)_f\frac{d\left[(H_w+H_0)(T_w+T_0)\right]}{dt}=\left[\lambda_x\frac{\partial T}{\partial x}-(\rho c)_f vT\right]\Big\vert_{x=0}$ $T_w(0)=T_{wo}$	$(\rho c)_f\frac{\partial T}{\partial t}=\frac{1}{r}\frac{\partial}{\partial x}\left[\lambda_r r\frac{\partial C}{\partial r}-(\rho c)_f vrT\right]$ $\lambda_x=\lambda_p+\lambda_{vr}$ $\lambda_p=(\rho c)_{fs}\left[n\frac{\lambda_f}{(\rho c)_f}+(1-n)\frac{\lambda_s}{(\rho c)_s}\right]$ $\lambda_p=n\lambda_f+(1-n)\lambda_s$ $\lambda_{vr}=\alpha_{hr}(\rho c)_f v$ $T(r,0)=T_0$ $T(L,t)=T_0$ $T(0,t)=T_w(t)+T_0$ $(\rho c)_f\frac{d\left[(H_w+H_0)(T_w+T_0)\right]}{dt}=\frac{2b}{r_w}\left[\lambda_r\frac{\partial T}{\partial r}-(\rho c)_f vT\right]\Big\vert_{x=0}$ $T_w(0)=T_{wo}$

3. Theory and Methods

Well-posed Problem

$$\begin{cases} \dfrac{\partial T}{\partial t} = \alpha \dfrac{\partial^2 T}{\partial x^2} & 0 < x < L, t > 0 \\ T(x,0) = T_0 & 0 < x < L \\ T(L,t) = T_0 & t \geqslant 0 \\ T(0,t) = T_A + T_0 & t \geqslant 0 \end{cases}$$

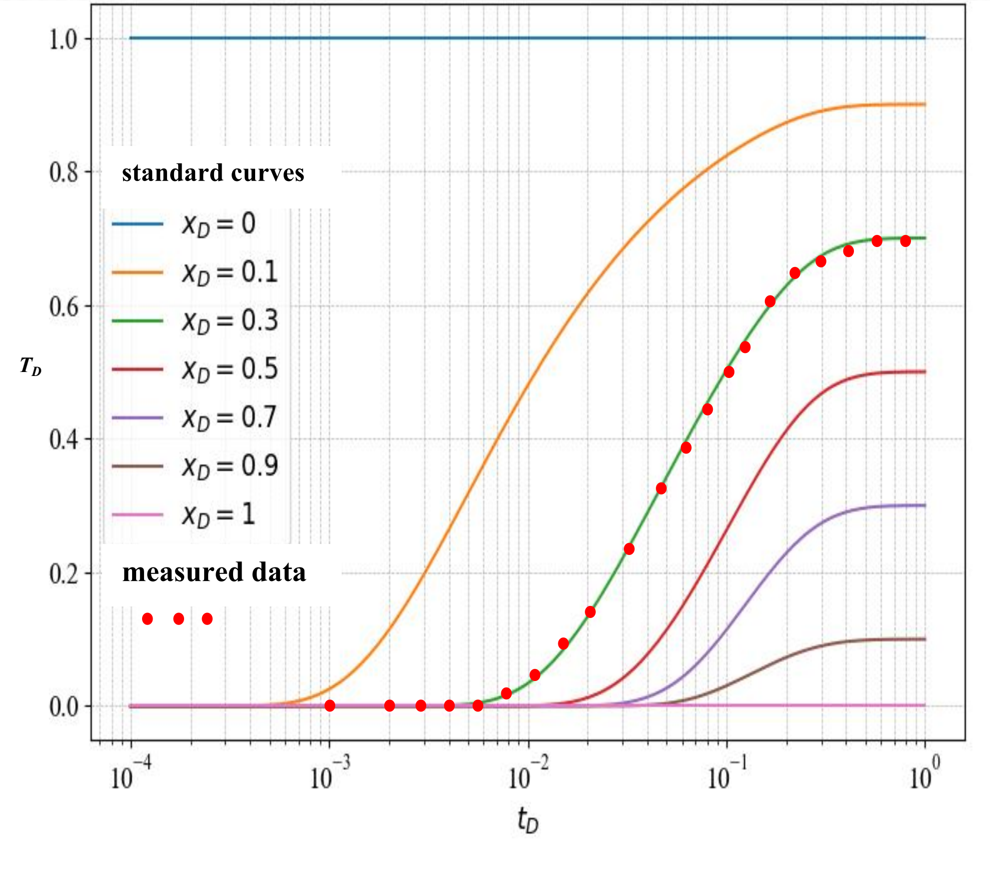
Dimensionless Factors

$$\begin{cases} x_D = \dfrac{x}{L} \\ T_D = \dfrac{T - T_0}{T_A} \\ t_D = \dfrac{D_0 t}{L^2} \end{cases}$$

Separation of Variables

$$T_D(x_D, t_D) = (1 - x_D) - \sum_{n=1}^{\infty} \frac{2}{n\pi} e^{-(n\pi)^2 t_D} \sin(n\pi x_D)$$

$$T(x,t) = T_0 + T_A \left[\left(1 - \frac{x}{L}\right) - \sum_{n=1}^{\infty} \frac{2}{n\pi} e^{-(n\pi)^2 \frac{D_0 t}{L^2}} \sin\left(\frac{n\pi x}{L}\right) \right]$$



Analytical Solution

3. Theory and Methods

Well-posed Problem

$$\begin{cases} \dfrac{\mu^*}{T}\dfrac{\partial H}{\partial t} = \dfrac{\partial^2 H}{\partial r^2} + \dfrac{1}{r}\dfrac{\partial H}{\partial r} & r_s < r < r_L, t > 0 \\ H(r,0) = H_0 & r_s < r \leqslant r_L \\ H(r_L,t) = H_0 & t > 0 \\ H(r_s,t) = w(t) + H_0 & t \geqslant 0 \\ \pi r_c^2 \dfrac{dw}{dt} = 2\pi r_s T \dfrac{\partial H}{\partial r}\Big|_{r=r_s} & t \geqslant 0 \\ w(0) = w_0 & t = 0 \end{cases}$$

Dimensionless Factors

$$\begin{cases} r_D = \dfrac{r}{r_s} \\ r_{LD} = \dfrac{r_L}{r_s} \\ H_D = \dfrac{H - H_0}{w_0} \\ w_D = \dfrac{w}{w_0} \\ t_D = \dfrac{Tt}{r_c^2} \\ \mu_D^* = \dfrac{r_s^2}{r_c^2}\mu^* \\ s^* = \sqrt{\mu_D^* s} \end{cases}$$

Dimensionless Transformation

$$\begin{cases} \mu_D^* \dfrac{\partial H_D}{\partial t_D} = \dfrac{\partial^2 H_D}{\partial r_D^2} + \dfrac{1}{r_D}\dfrac{\partial H_D}{\partial r_D} & 1 < r_D < r_{LD}, t_D > 0 \\ H_D(r_D,0) = 0 & 1 \le r_D \le r_{LD} \\ H_D(r_{LD},t_D) = 0 & t_D > 0 \\ H_D(1,t_D) = w_D(t_D) & t_D \ge 0 \\ \dfrac{dw_D}{dt_D} = 2\dfrac{\partial H_D}{\partial r_D}\Big|_{r_D=1} & t_D \ge 0 \\ w_D(0) = 1 \end{cases}$$

Laplace Transform

Frequency Domain Solution

$$\bar{w}_D(s) = \cfrac{1}{s + 2s^* \cfrac{I_0(s^* r_{LD})K_1(s^*) + I_1(s^*)K_0(s^* r_{LD})}{I_0(s^* r_{LD})K_0(s^*) - I_0(s^*)K_0(s^* r_{LD})}}$$

$$\tilde{H}_D(r_D,s) = \frac{K_0(s^* r_D)I_0(s^* r_{LD}) - K_0(s^* r_{LD})I_0(s^* r_D)}{K_0(s^*)I_0(s^* r_{LD}) - K_0(s^* r_{LD})I_0(s^*)}\bar{w}_D(s)$$

Semi-analytical Solution

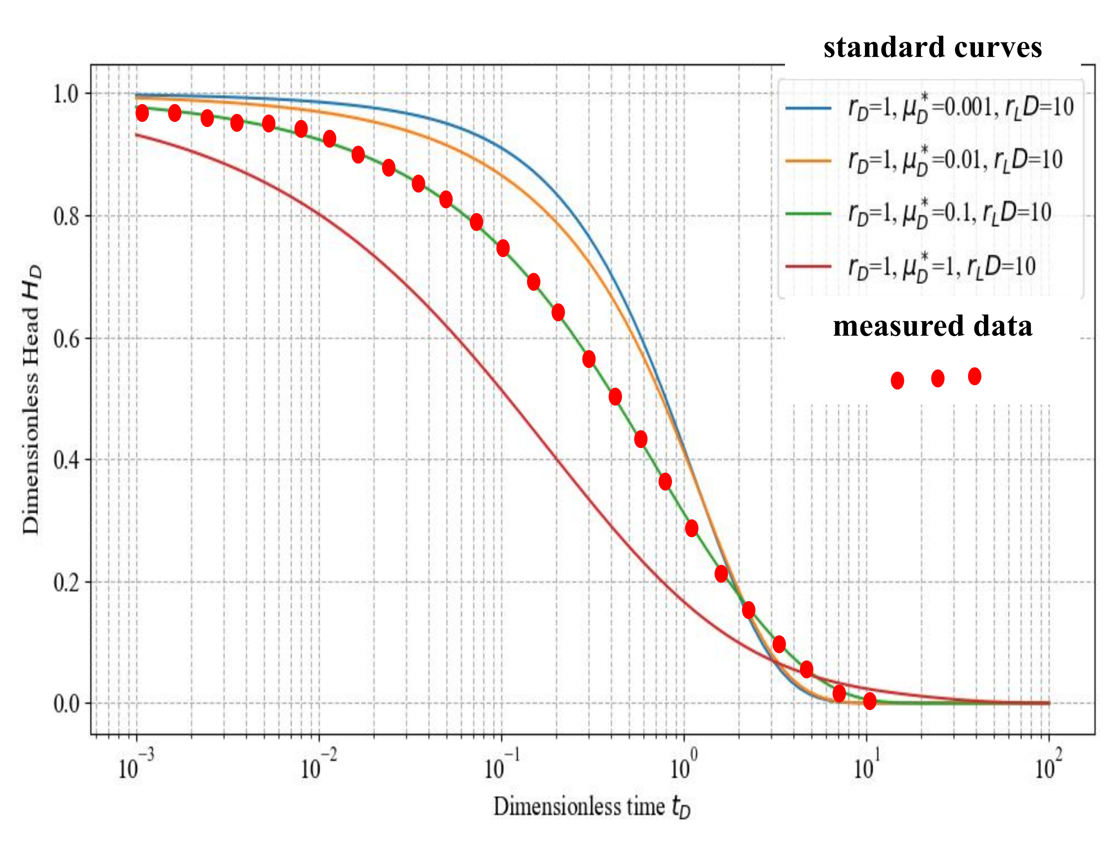
3. Theory and Methods

Laplace Inverse Transform

Stehfest Method

$$w_D(t_D) \approx \frac{\ln 2}{t_D} \sum_{n=1}^{N} V_n \bar{w}_D\left(\frac{n \ln 2}{t_D}\right)$$

$$V_n = (-1)^{n+N/2} \sum_{k=[(n+1)/2]}^{\min(n,N/2)} \frac{k^{N/2}(2k)!}{(N/2-k)!k!(k-1)!(n-k)!(2k-n)!}$$



Semi-analytical Solution

3. Theory and Methods

Well-posed Problem

$$\begin{cases} \mu_s \dfrac{\partial H}{\partial t} = K\dfrac{\partial^2 H}{\partial x^2} \\ H(x,0) = H_0 \\ H(L,t) = H_0 \\ H(0,t) = w(t) + H_0 \\ \dfrac{dw}{dt} = K\dfrac{\partial H}{\partial x}\Big|_{x=0} \\ w(0) = w_0 \\ u(x,t) = -\dfrac{1}{n}K\dfrac{\partial H}{\partial x} \\ \dfrac{\partial C}{\partial t} = \dfrac{\partial}{\partial x}\left(D_L\dfrac{\partial C}{\partial x}\right) - \dfrac{\partial}{\partial x}(uC) \\ D_L = D_0 + \alpha_L u \\ C(x,0) = C_0 \\ C(L,t) = C_0 \\ C(0,t) = C_w(t) + C_0 \\ \dfrac{d\left[(w+h_0)\cdot(C_w + C_0)\right]}{dt} = n\left(D_L\dfrac{\partial C}{\partial x} - uC\right)\Big|_{x=0} \\ C_w(0) = C_{w0} \end{cases}$$

Dimensionless Factors

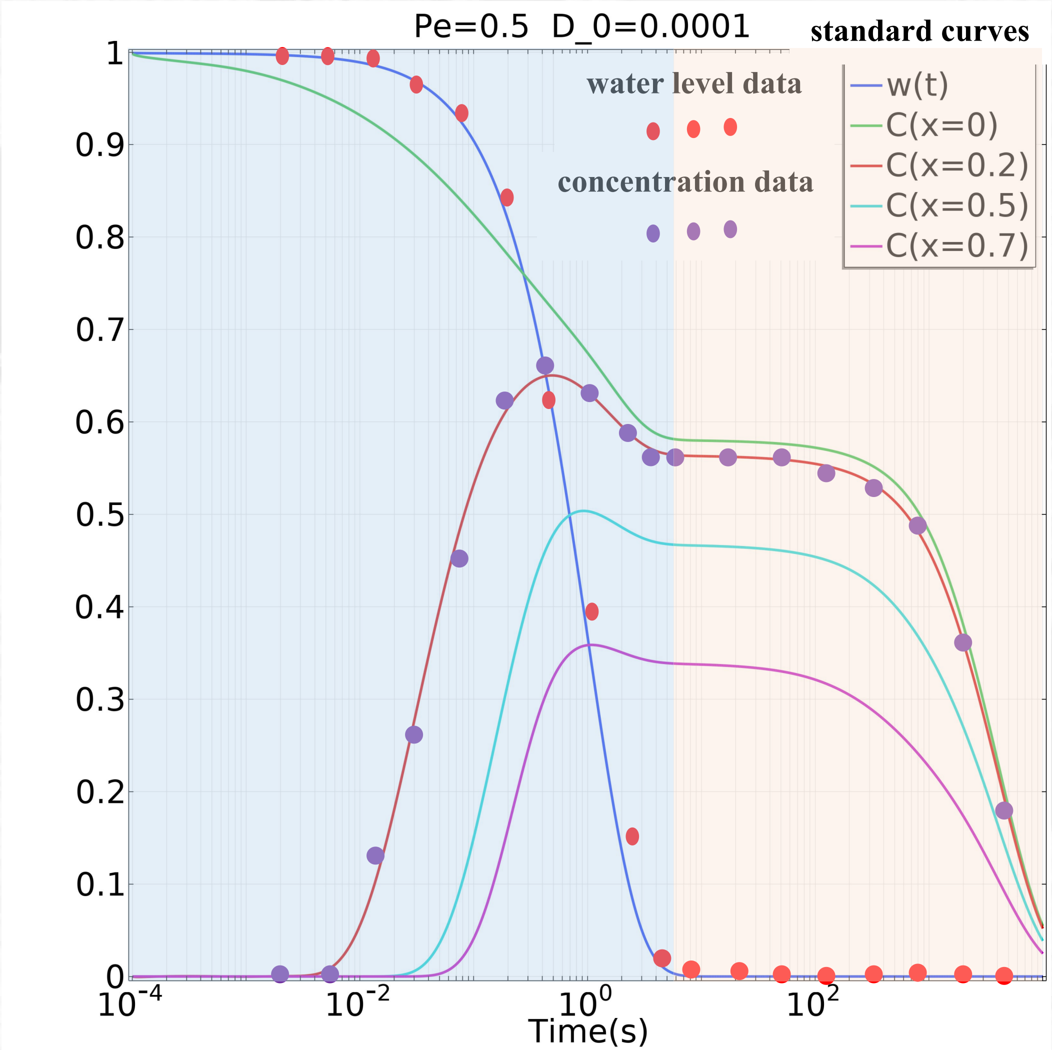
$$\begin{cases} H_0 = \dfrac{H - H_0}{w_0} \\ x_D = \dfrac{x}{L} \\ C_D = \dfrac{C - C_0}{C_{w_0}} \\ w_D = \dfrac{w}{w_0} \\ C_{w_D} = \dfrac{C_w}{C_{w_0}} \\ t_D = \dfrac{Kt}{L} \\ \mu_{sD} = \mu_s L \\ C_{0D} = \dfrac{C_0}{C_{w_0}} \\ D_{LD} = \dfrac{D_L}{KL} \\ u_D = \dfrac{u}{K} \\ D_{0D} = \dfrac{D_0}{KL} \\ Pe = \dfrac{\alpha_L}{L} \\ h_{0D} = \dfrac{h_0}{w_0} \\ n_D = \dfrac{nL}{w_0} \end{cases}$$

Dimensionless Transformation

$$\begin{cases} \mu_{sD}\dfrac{\partial H_D}{\partial t_D} = \dfrac{\partial^2 H_D}{\partial x_D^2} \\ H_D(x_D,0) = 0 \\ H_D(L,t_D) = 0 \\ H_D(0,t_D) = w_D(t_D) \\ \dfrac{dw_D}{dt_D} = \dfrac{\partial H_D}{\partial x_D}\Big|_{x_D=0} \\ w_D(0) = 1 \\ u_D = -\dfrac{1}{n_D}\dfrac{\partial H_D}{\partial x_D} \\ \dfrac{\partial C_D}{\partial t_D} = \dfrac{\partial}{\partial x_D}\left[D_{LD}\dfrac{\partial C_D}{\partial x_D} - u_D(C_{0D} + C_D)\right] \\ D_{LD}(u_D) = D_{0D} + Pe u_D \\ C_D(x_D,0) = 0 \\ C_D(L,t_D) = 0 \\ C_D(0,t_D) = C_{wD}(t_D) \\ C_{wD}(0) = 1 \\ \dfrac{d\left[(w_D + h_{0D})C_{wD}\right]}{dt_D} = n_D\left[D_{LD}\dfrac{\partial C_D}{\partial x_D}C_D - u_D(C_{0D} + C_D)\right]\Big|_{x_D=0} \end{cases}$$

Numerical Solution (COMSOL)

3. Theory and Methods



Hydraulic Control

Molecular Diffusion Control

$$\begin{cases} K = \dfrac{[t_D]L}{[t]} \\ \mu_s = \dfrac{[\mu_{sD}]}{L} \\ \alpha_L = [Pe]L \\ D_0 = [D_{0D}]KL \\ D_L = D_0 + \alpha_L u \end{cases}$$

Multiple hydrogeological parameters can be calculated simultaneously by matching data from multiple fields in a single test

Numerical Solution (COMSOL)

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04 Conclusion

4. Conclusion

1. Coupled Model Validation

Combined experiments and simulations validate coupled hydraulic-thermal-solute models for reliable estimation of permeability, thermal conductivity, and dispersion coefficients.

2. Enhanced Parameter Accuracy

Synergistic experimental-numerical approaches improve parameter identification in multi-physics systems, resolving complex coupling mechanisms.

3. Robust Experimental Framework

High-precision laboratory measurements and cross-validation quantify spatiotemporal dynamics of coupled flow, heat, and solute transport.

Analytical solution+Indoor experiments+Numerical simulation

Thank you for your time and attention

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