Using a 3D thermo-hydro-mechanical coupling numerical model to evaluate the optimal configuration of geothermal wells: A case study of the Chingshui Geothermal Field

Presenter: Ching-Yuan Kao

Advisor: Prof. Shih-Jung Wang

Date: 2024/3/22

Outline

Introduction

Methodology

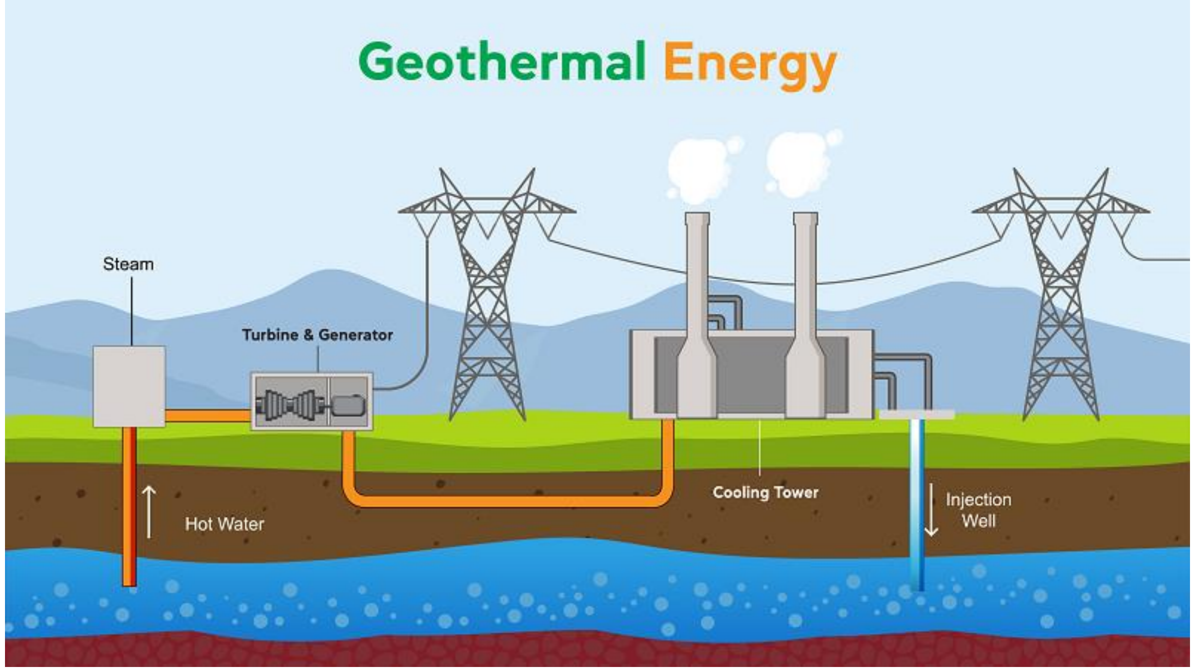
Results

Conclusions

Introduction

Introduction

◆ Geothermal energy



➢ Geothermal energy is heat energy from the earth.

➢ Geothermal resources are reservoirs of hot water that exist or are human made at varying temperatures and depths below the Earth's surface.

➢ Wells, ranging from a few meters to several kilometers deep, can be drilled into underground reservoirs to tap steam and very hot water that can be brought to the surface for use in a variety of applications, including electricity generation, direct use, heating and cooling.

Introduction

◆ Study area

The Chingshui geothermal field is located in Datong Township, Yilan County, and belongs to the Miocene Lushan Formation.

- ✓ Jentse Member Lsj

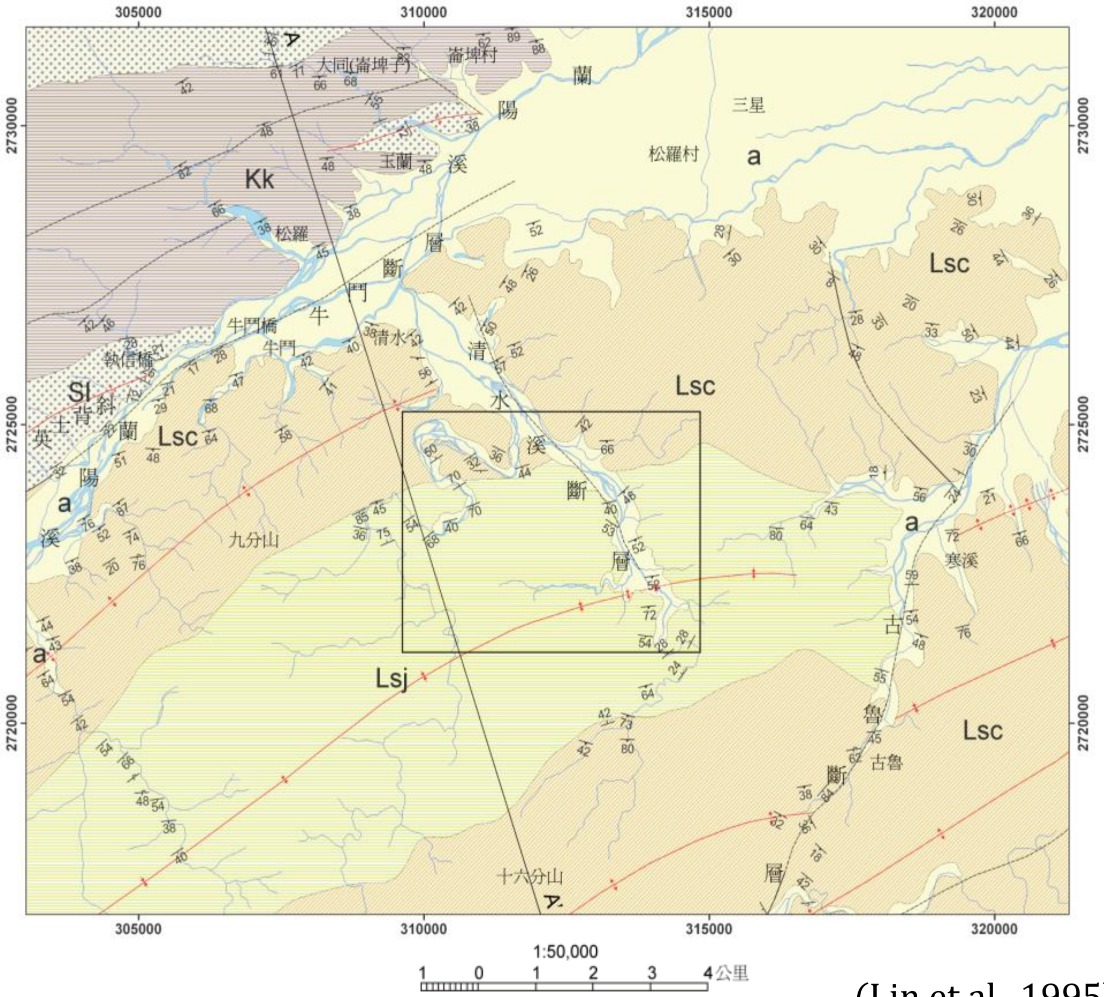
  Argillite or thin Interbeds of Argillite and Meta Sandstone.

- ✓ Chingshuihu Member Lsc

  Argillite or Slate, Occasionally Intercalated with thin Layers of Meta Sandstone.

- ✓ Chingshuihsi fault

  The width of the fracture zone is around 200 meters. Considered an important conduit for guiding the upward flow of heat.



(Lin et al., 1995)

Introduction

◆ Objective

- Exploring the impact of thermo-hydro-mechanical coupling in geothermal production processes.

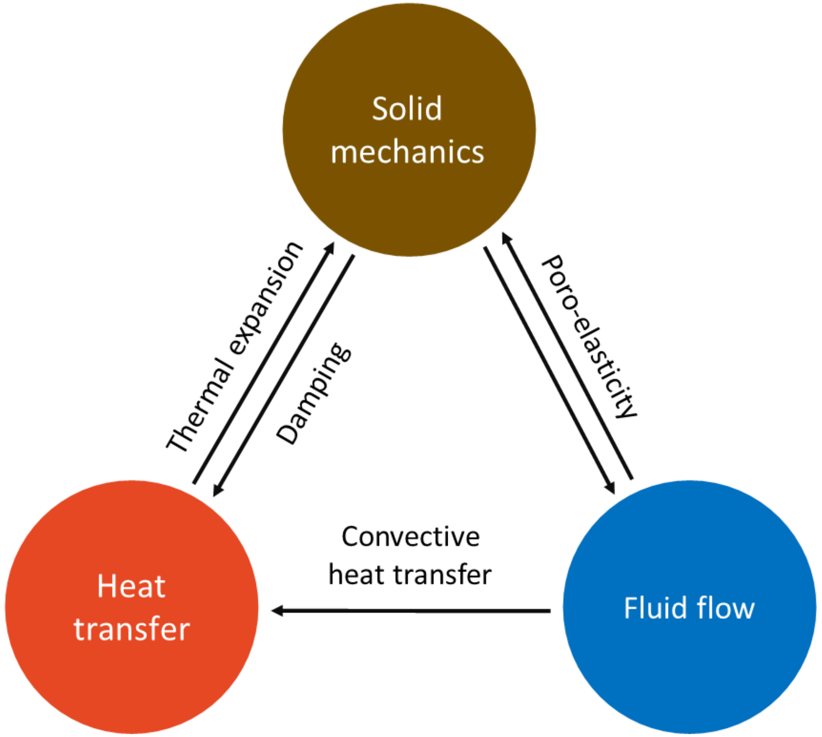
- Observing the impact of different parameters (permeability, pumping rate, injection water temperature, etc.) on simulation results.

◆ Methods

- Using COMSOL Multiphysics to create a three-dimensional numerical model, select the modules "Solid Mechanics," "Heat Transfer in Porous Media," and "Darcy's Law" to respectively establish displacement field, temperature field, and flow field. The calculated dependent variables are displacement, temperature, and water pressure.

Introduction

◆ Thermo-Hydro-Mechanical coupling



Governing equations

❖ $\rho_f \alpha \frac{\partial}{\partial t}(\nabla \cdot \boldsymbol{u}) + \rho_f S \frac{\partial p}{\partial t} + \nabla \cdot \rho_f(-\frac{k}{\mu} \nabla p) = Q_m$ (mass conservation)

❖ $G \nabla^2 u_i + \frac{G}{1-2\mathbf{v}} \frac{\partial^2 u_k}{\partial x_i \partial x_k} = \alpha \frac{\partial p}{\partial x_i} + C : a_T(T - T_{ref}) - (\rho_s + n\rho_f)g$ (force equilibrium)

❖ $(c\rho)_{eff} \frac{dT}{dt} + c_f \rho_f(-\frac{k}{\mu} \nabla p) \nabla T + \nabla \cdot (-k_{T_{eff}} \nabla T) = Q_T + \tau : \nabla(-\frac{k}{\mu} \nabla p) + Q_{ted}$ (energy conservation)

ρ: Density
n: Porosity
S: Storage coefficient
p: Pore water pressure
α: Biot coefficient

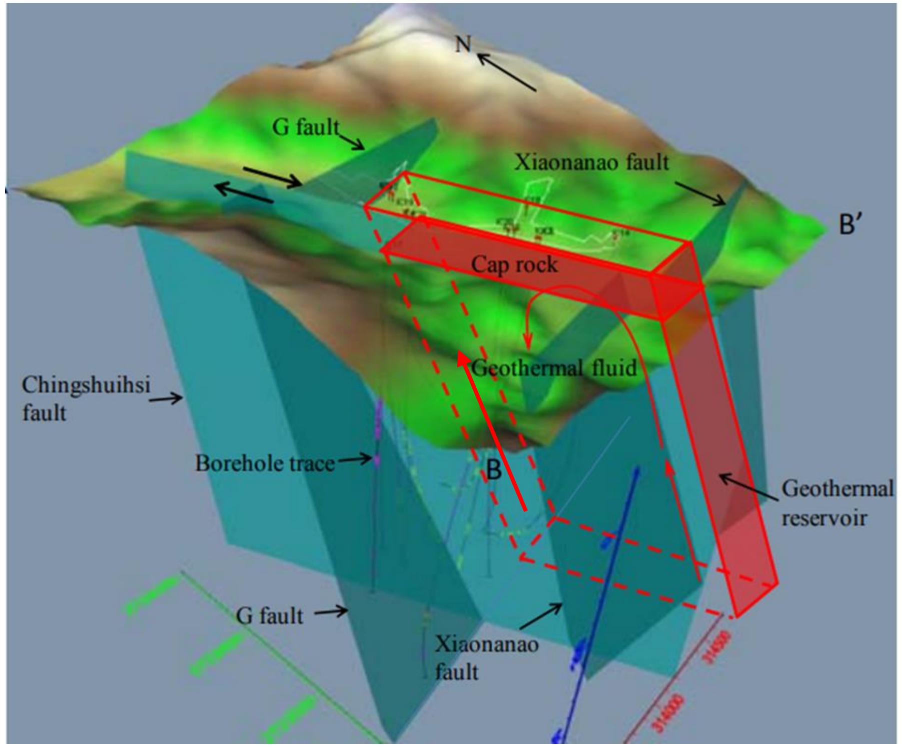
G: Shear modulus
u: Displacement
$\mathbf{v}$: Poisson ratio
x: Length
C: Stress tensor

a_T: Coefficient of thermal expansion
c: Heat capacity
k_T: Thermal conductivity
Q_{ted}: Heat source from thermoelastic damping

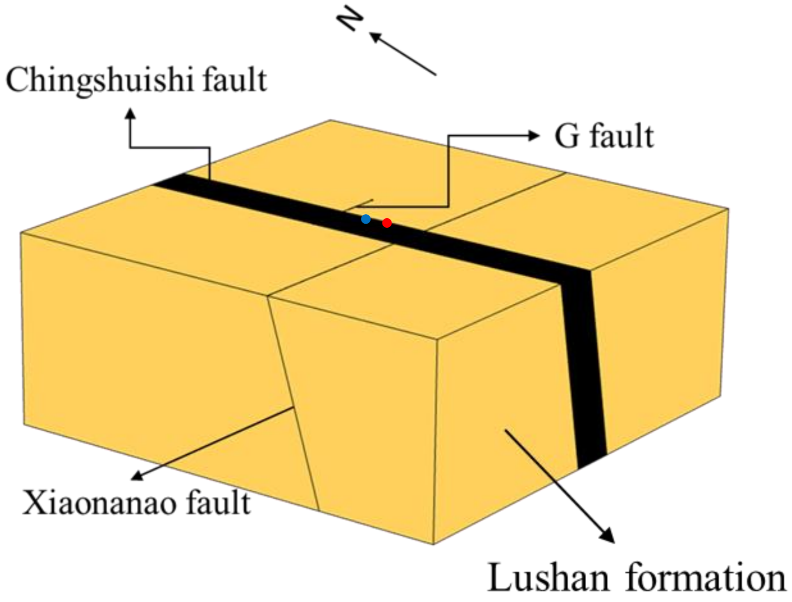
Methodology

Methodology

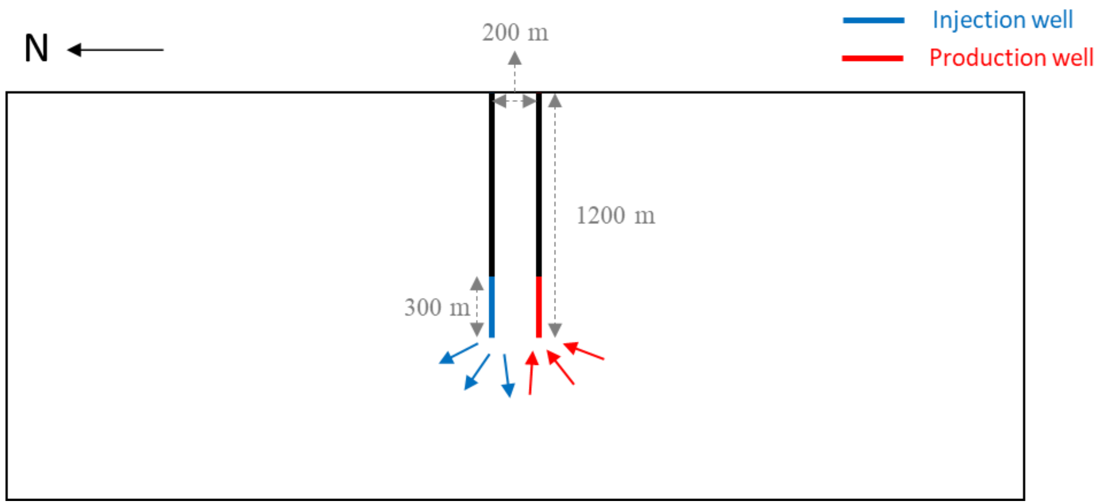
◆ Conceptual model & Geological model



⬆ Conceptual model of Chingshui geothermal field (Lee et al., 2012)



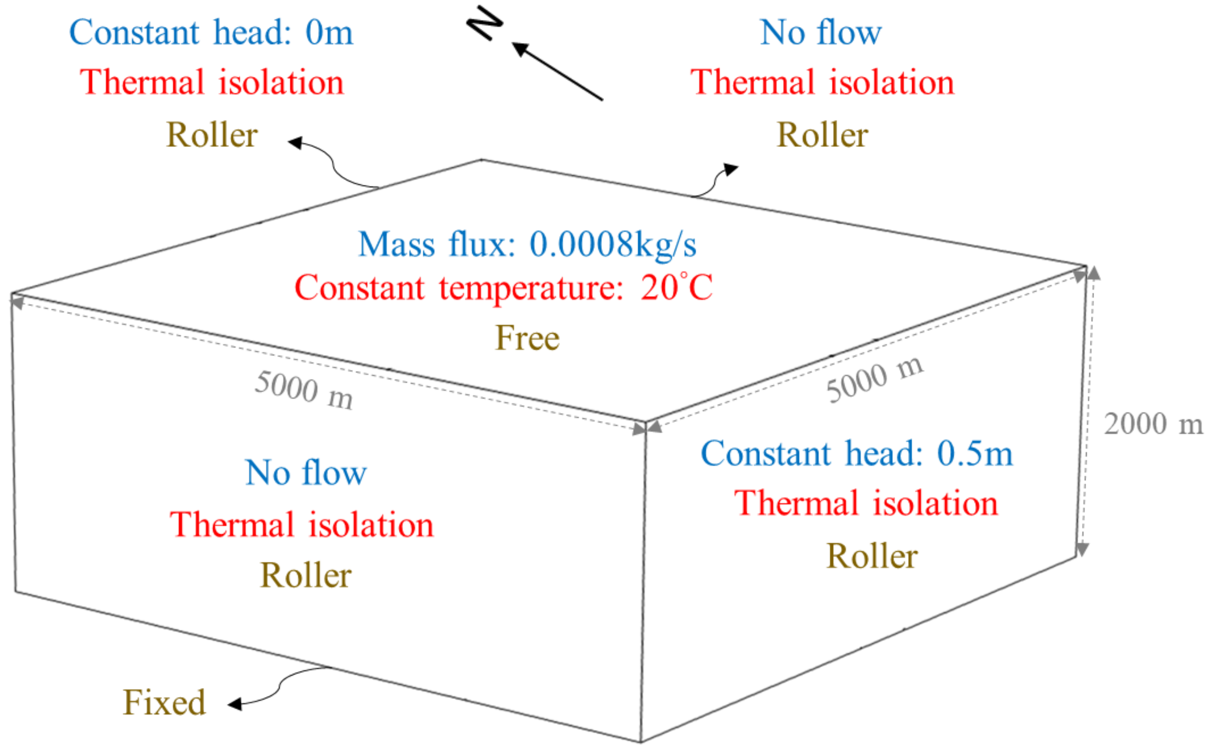
⬆ Simplified geological model



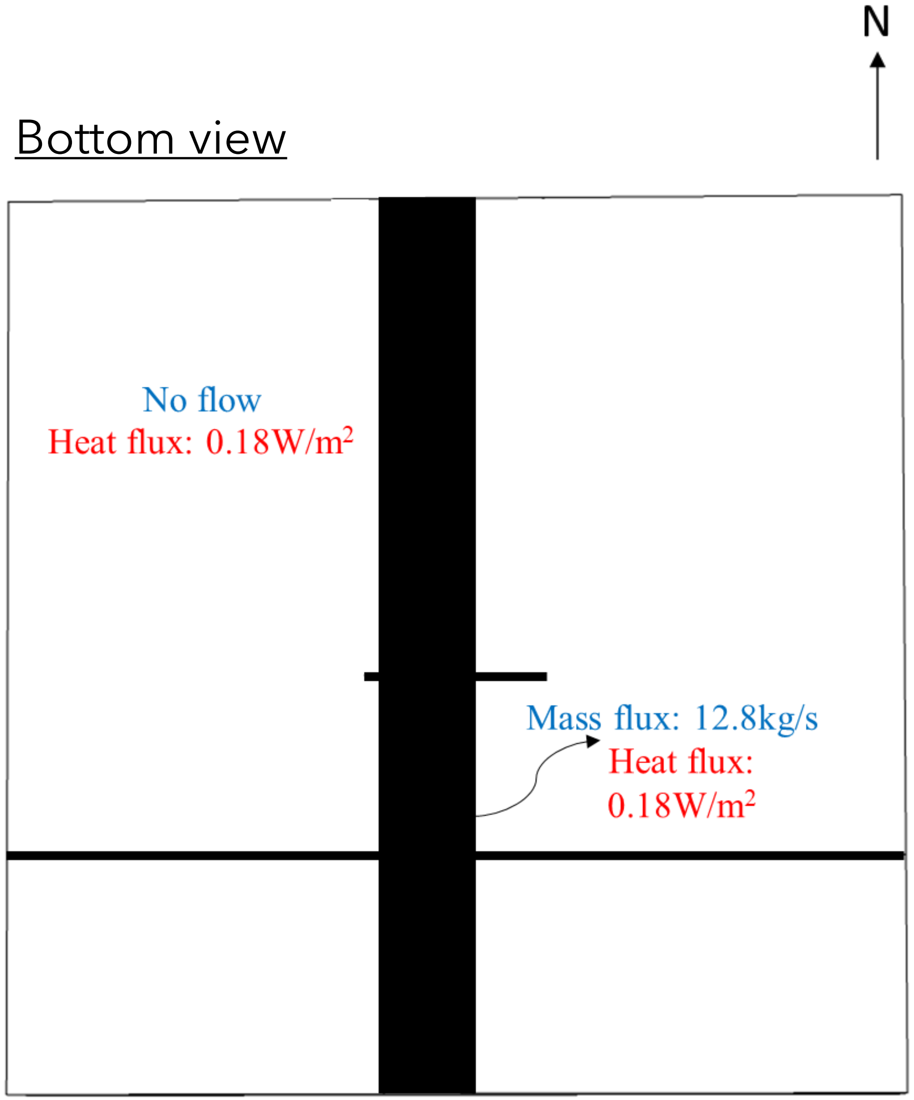
⬆ Injection & production well (doublet system)

Methodology

◆ Boundary conditions



Bottom view



Methodology

◆ Initial conditions & parameter settings

- Given the model with a top boundary temperature of 20 °C and an increasing geothermal gradient (60°C /km) from top to bottom.

- Given the model a hydraulic gradient (1 mm/m), causing groundwater flow from south to north.

Fluid & Matrix parameter settings

Parameter	Unit	Fluids
		Water (20°C)
Density	$\frac{kg}{m^3}$	997.03
Compressibility	$\frac{1}{Pa}$	4.44×10^{-10}
Dynamic viscosity	$Pa \cdot s$	8.925×10^{-4}
Heat capacity	$\frac{J}{kg \cdot K}$	4200
Thermal conductivity	$\frac{W}{m \cdot K}$	0.6

Parameter	Unit	Matrix			
		Lushan Formation	**Chingshuishi fault**	**Xiaonanao fault**	**G fault**
Density	$\frac{kg}{m^3}$	2700			
Porosity	–	0.015	0.05	0.05	0.1
Young’s modulus	Pa	3.17×10^{10}			
Poisson ratio	–	0.31			
Permeability	m^2	10^{-16}	10^{-14}	10^{-14}	10^{-8}
Thermal conductivity	$\frac{W}{m \cdot K}$	3			
Heat capacity	$\frac{J}{kg \cdot K}$	800			
Thermal expansion coefficient	$\frac{1}{K}$	13×10^{-6}			

Methodology

◆ Sensitivity analysis

- The parameter sensitivity analysis in this study involved varying parameters such as **permeability**, **Young's modulus**, geothermal well **pumping rate**, and **injection water temperature** by **±50%** from the Reference parameters to observe their impact on the simulation results (production temperature and water pressure around production well).

- Considering that **Young's modulus**, **permeability**, and **coefficient of thermal expansion** typically span several orders of magnitude within the same material, their parameter ranges were set to be within positive and negative one order of magnitude.

Methodology

Parameter	Unit	Reference parameters				Parameter change range
		Lushan Formation	**Chingshuishi fault**	**Xiaonanao fault**	**G fault**	
Permeability	m^2	10^{-16}	10^{-14}	10^{-14}	10^{-8}	[k-, k+]=REF × [0.1, 1.0]
Porosity	$-$	0.015	0.05	0.05	0.1	[n-, n+]=REF × [0.5, 1.5]
Young's modulus	Pa	3.17×10^{10}				[E-, E+]=REF × [0.1, 1.0]
Poisson's ratio	$-$	0.31				[$\mathbf{v}$-,$\mathbf{v}$+]=REF × [0.5, 1.5]
Heat capacity	$\frac{J}{kg \cdot K}$	800				[c-, c+]=REF × [0.5, 1.5]
Coefficient of thermal expansion	$\frac{1}{K}$	13×10^{-6}				[α_T-,α_T+]=REF × [0.1, 1.0]
Injection temperature	$°C$	60				[T_{inj}-,T_{inj}+]=REF × [0.5, 1.5]
Pumping rate	$\frac{ton}{hr}$	60				[R_p-,R_p+]=REF × [0.5, 1.5]

⬆ The parameter settings & change range for the reference parameters

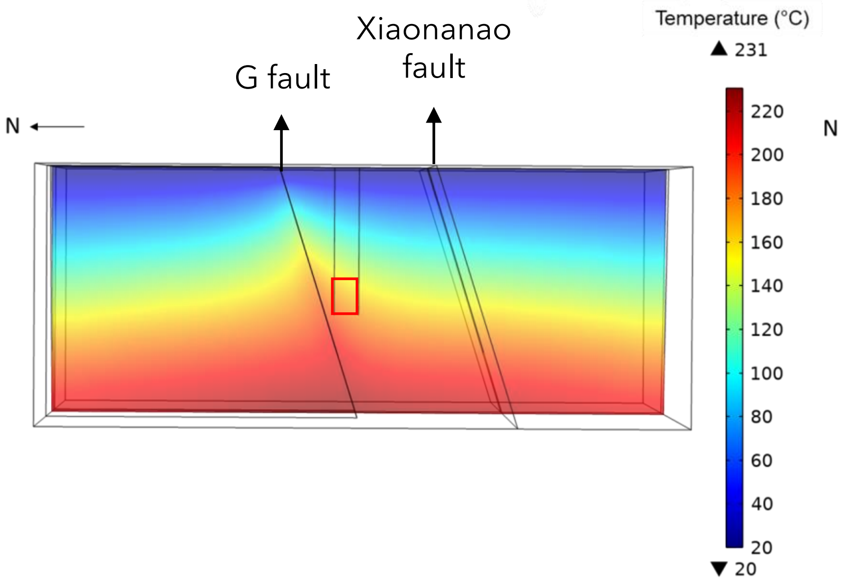
Results

Results

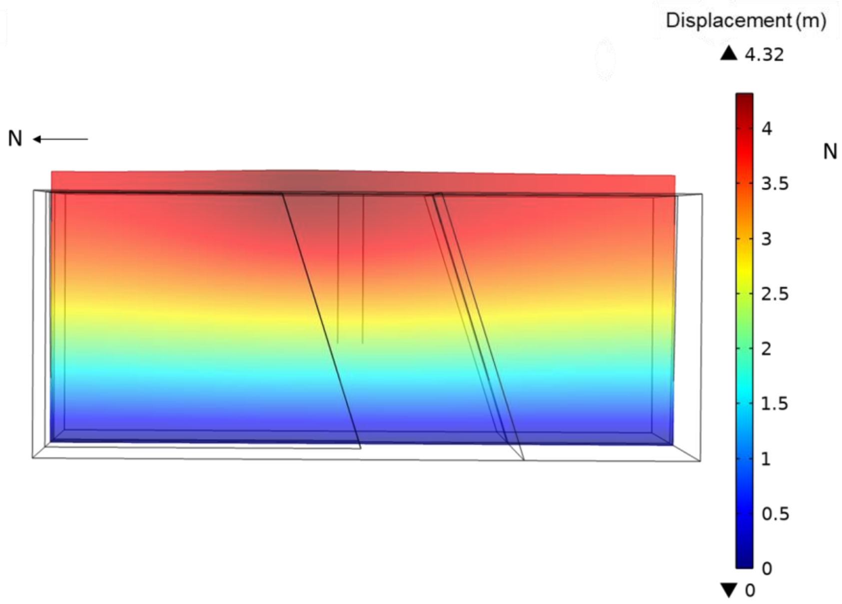
✓ In a steady-state simulation, the model ran for **0.2 million years** until all the physical fields reached a **steady state**.

◆ Steady-state simulation

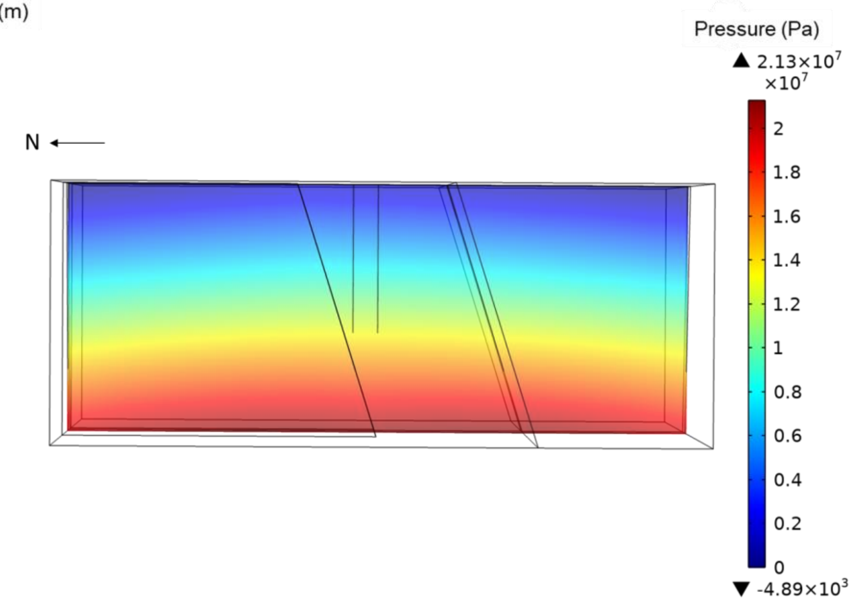
➢ Temperature distribution



➢ Displacement distribution



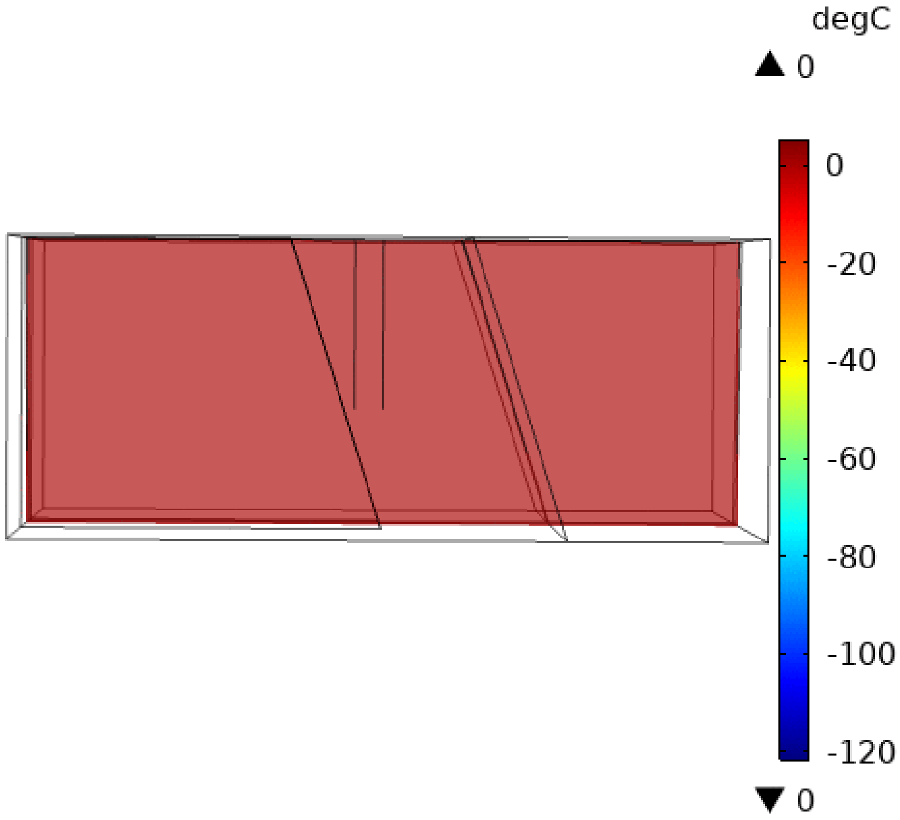
➢ Pressure distribution



Results

◆ Transient simulation

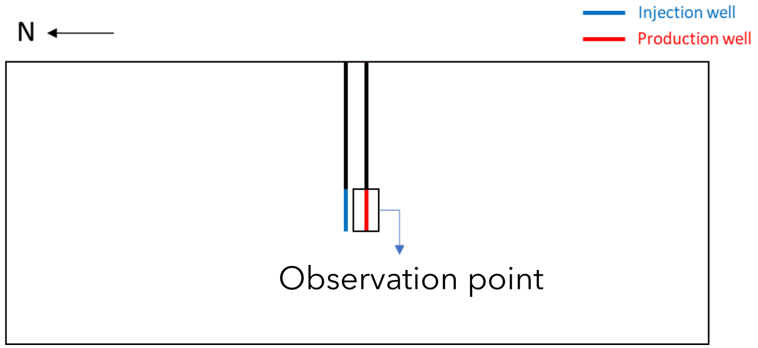
✓ In a transient simulation, the **geothermal well was activated** to begin pumping, and the simulation ran for 20 years.

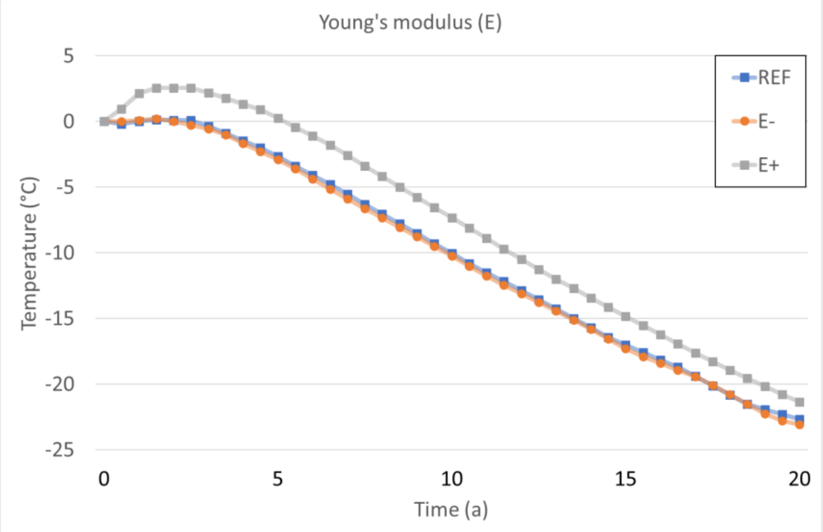


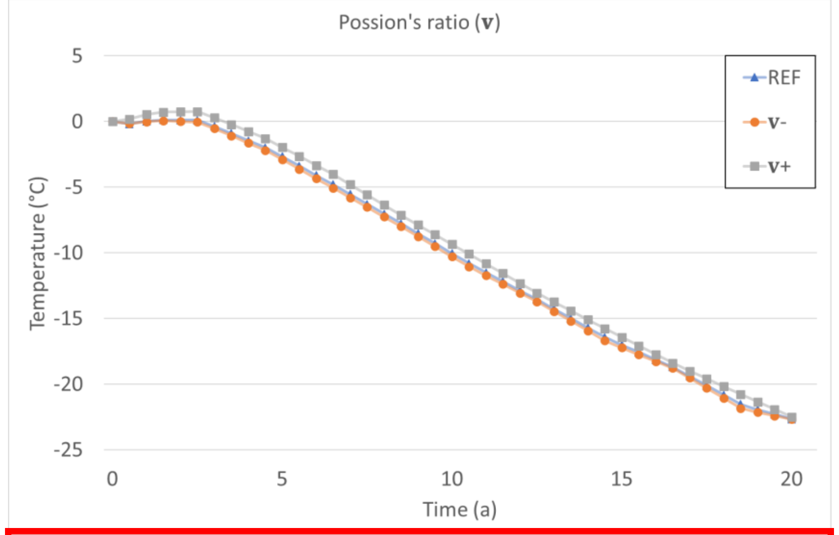
Temperature changes during cold water injection

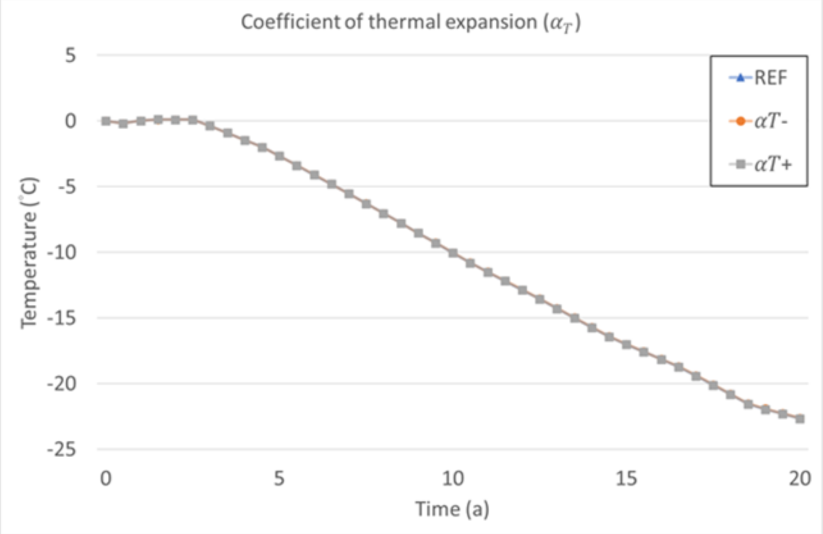
Results

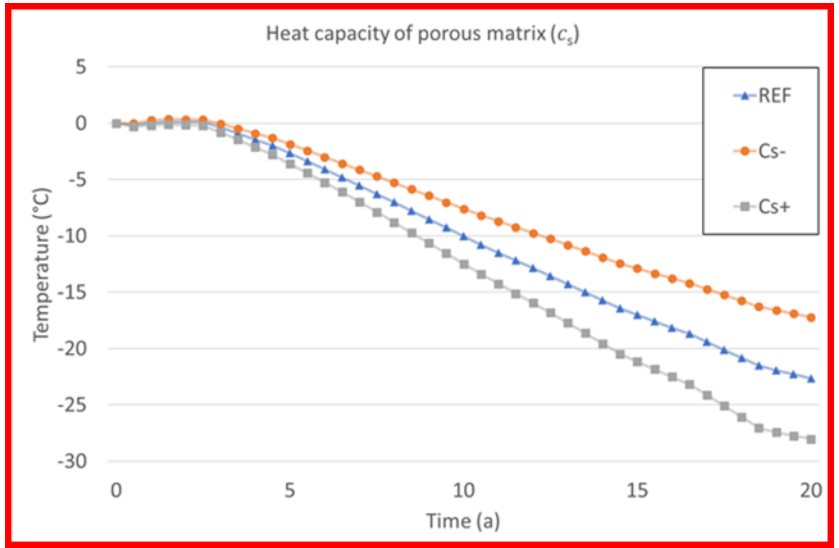
◆ Impact on production temperature





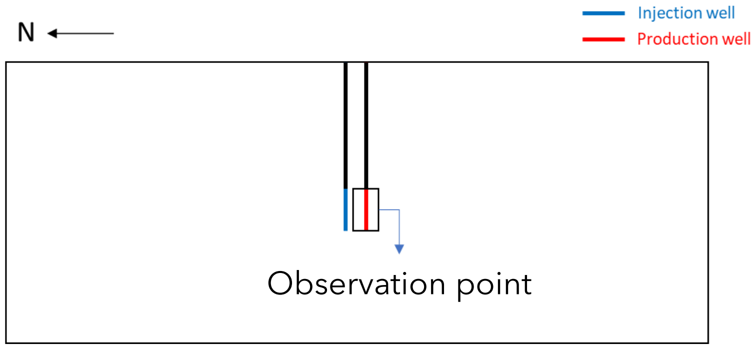


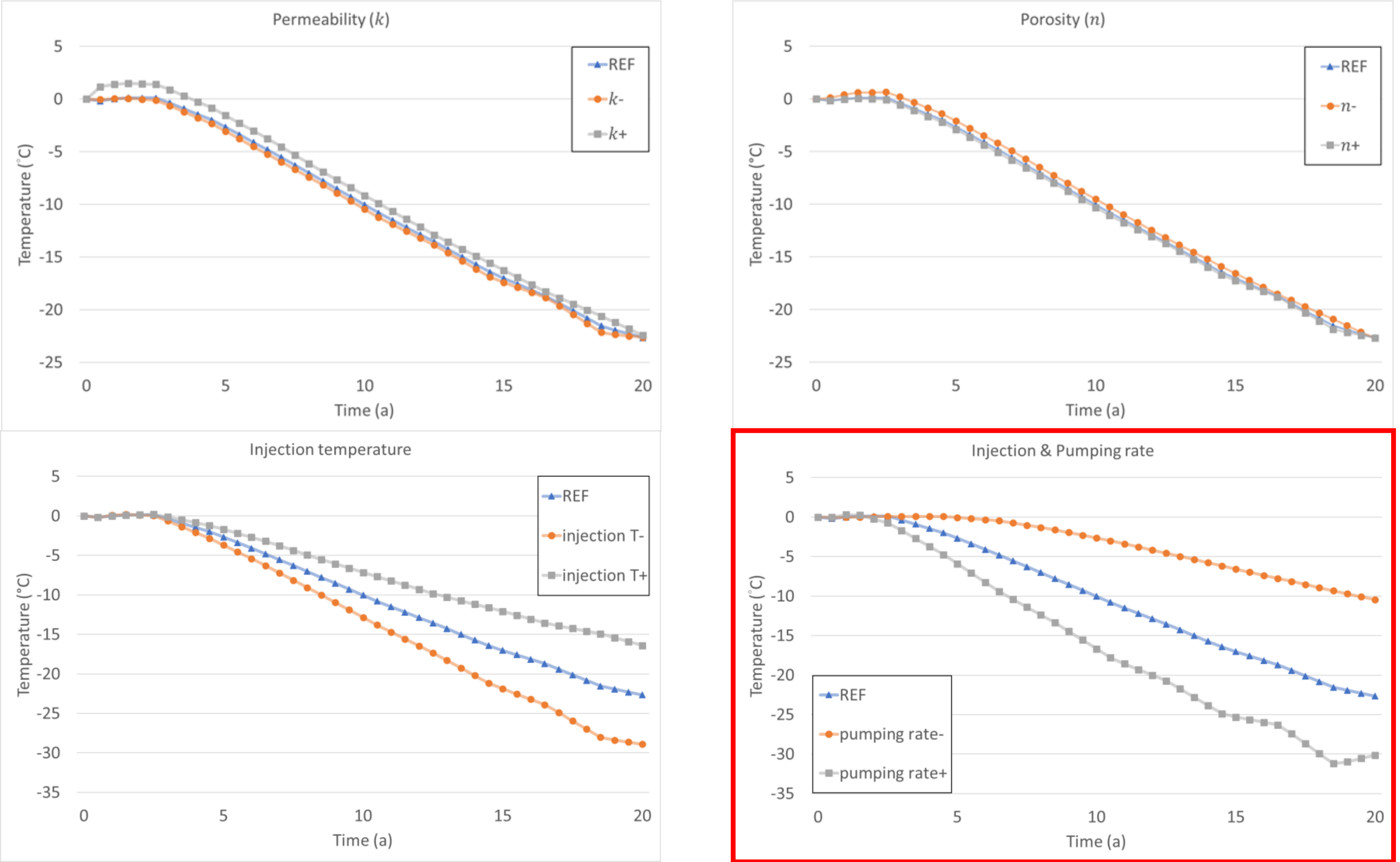




Results

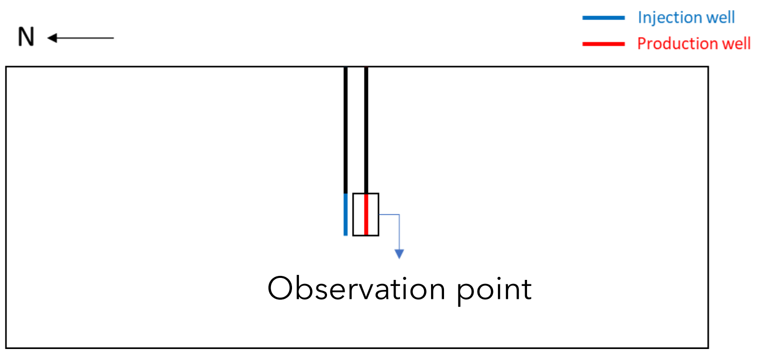
◆ Impact on production temperature

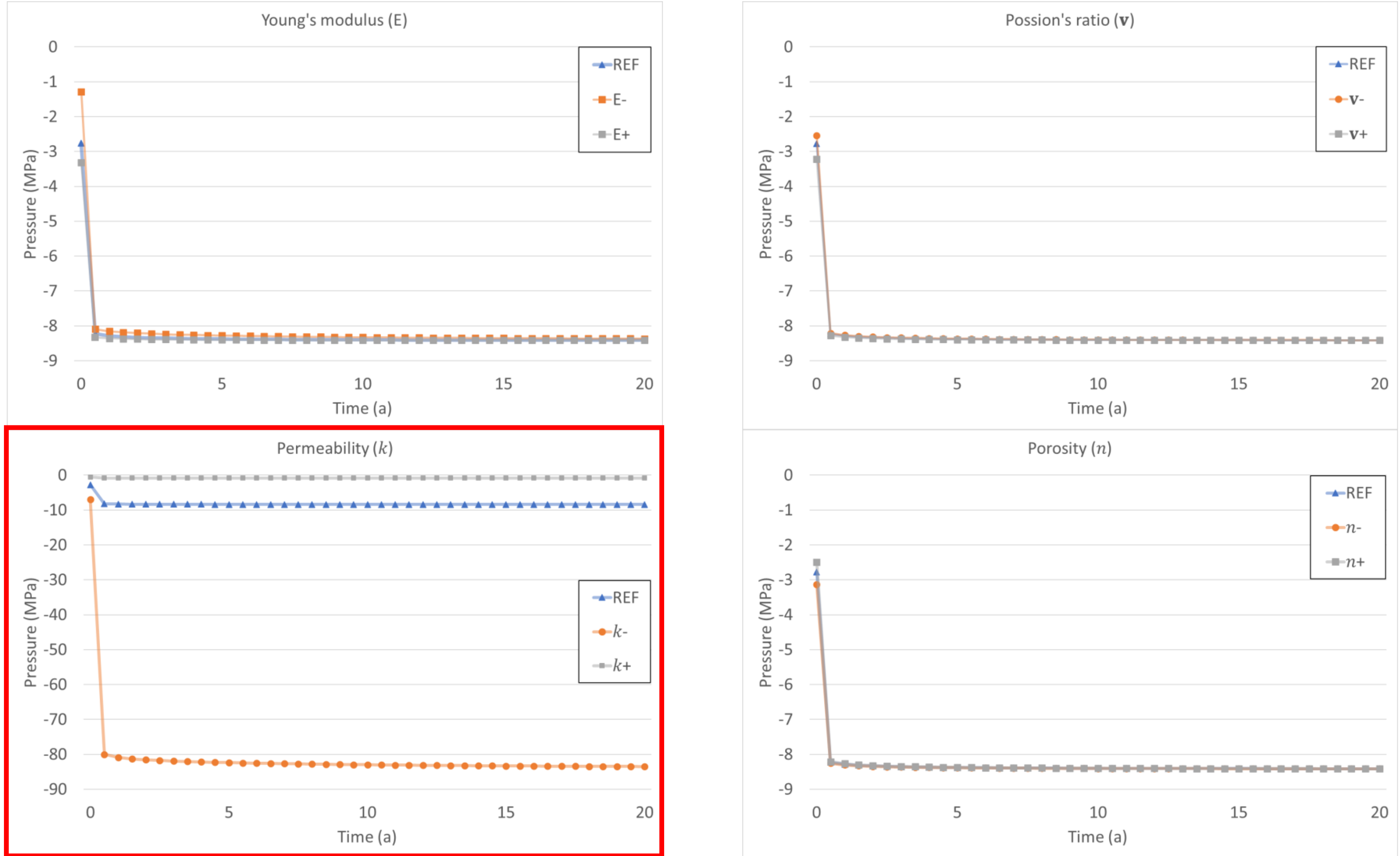




Results

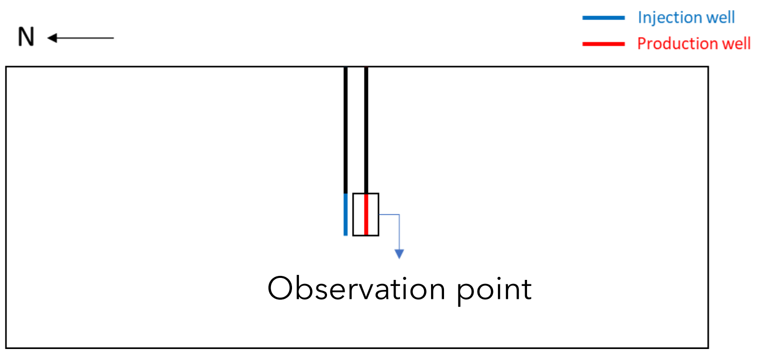
◆ Impact on water pressure around production well

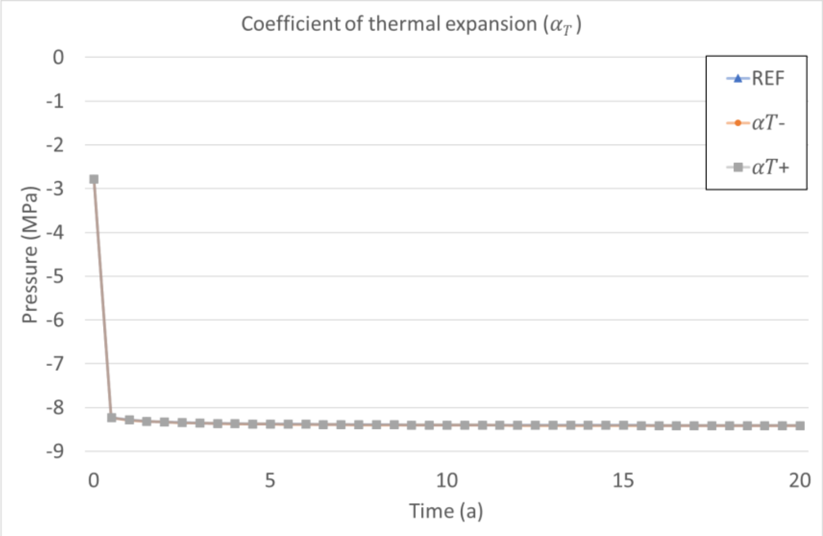


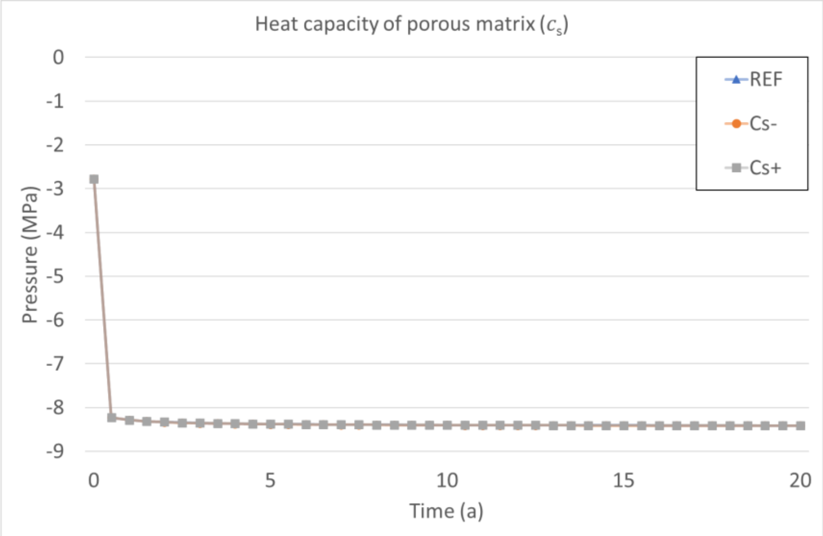


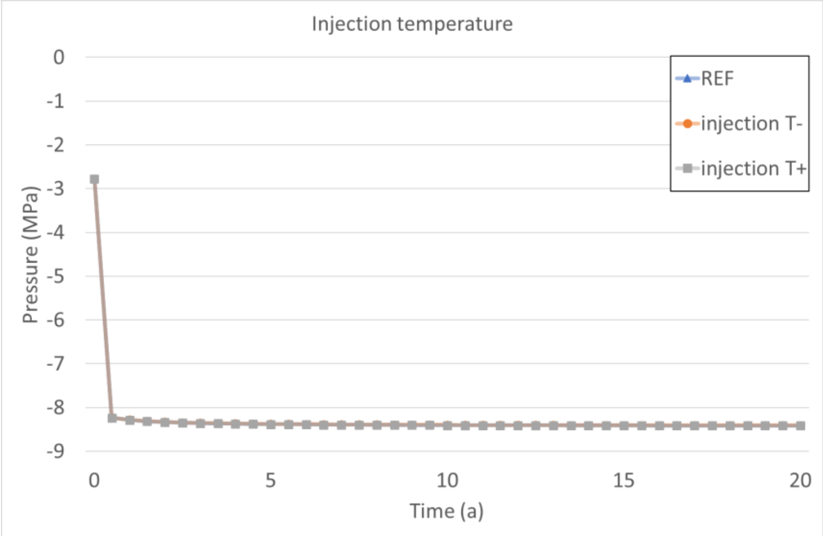
Results

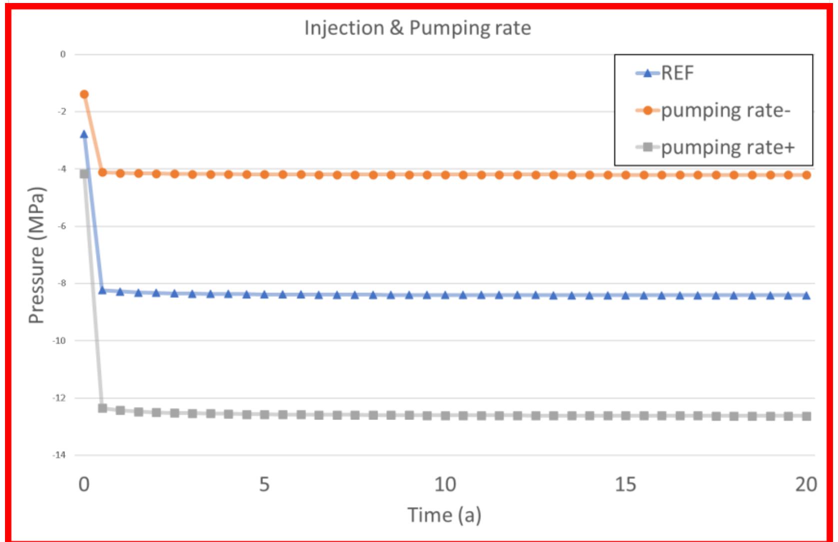
◆ Impact on water pressure around production well











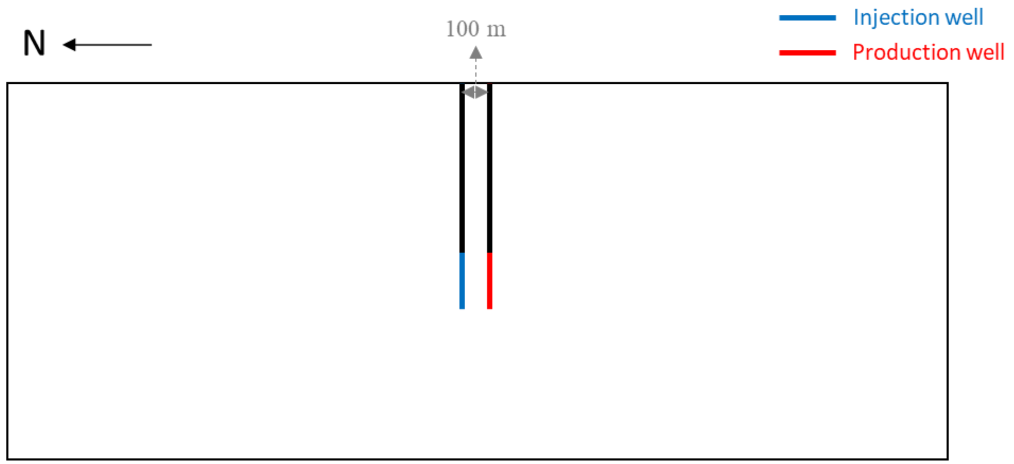
Conclusions

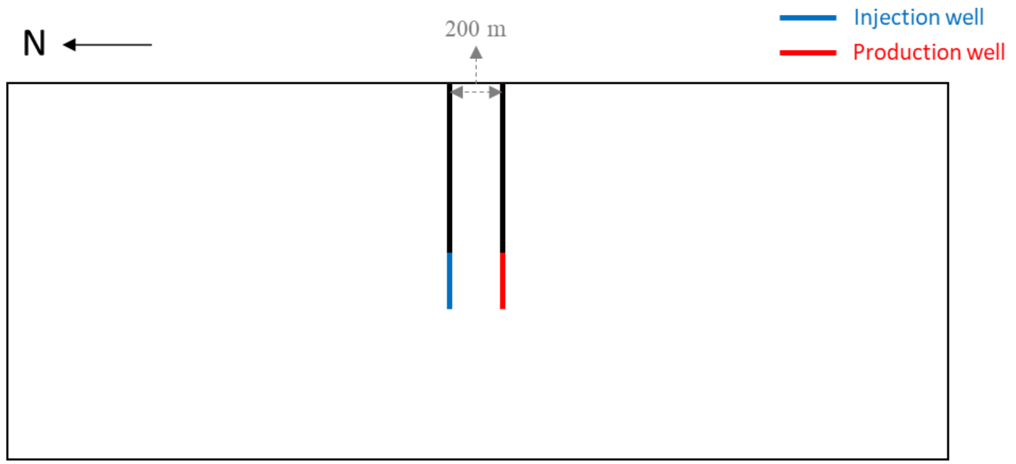
Conclusions

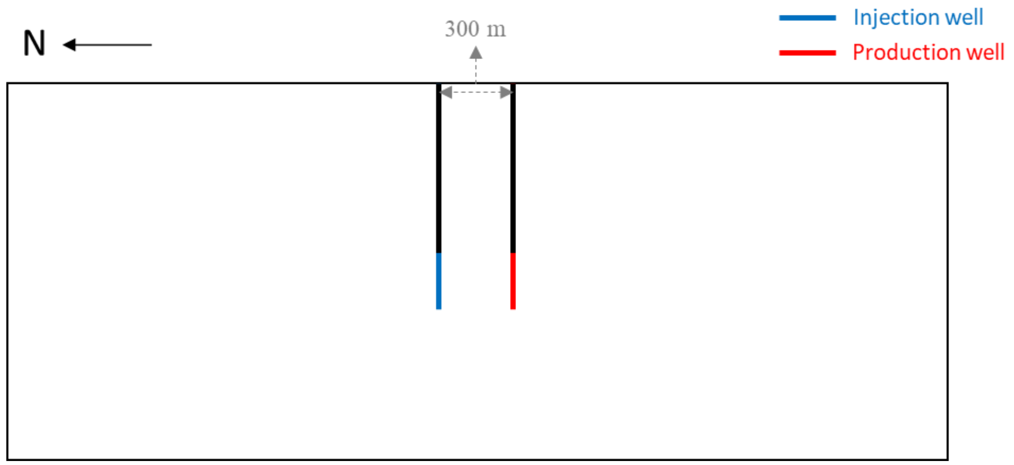
- This study successfully established a thermo-hydro-mechanical coupled numerical model. The results of parameter sensitivity analysis indicate that the production temperature exhibits higher sensitivity to **pumping rate and heat capacity**, while **pumping rate** and **permeability** exhibit higher sensitivity to variations in surrounding water pressure of production wells.

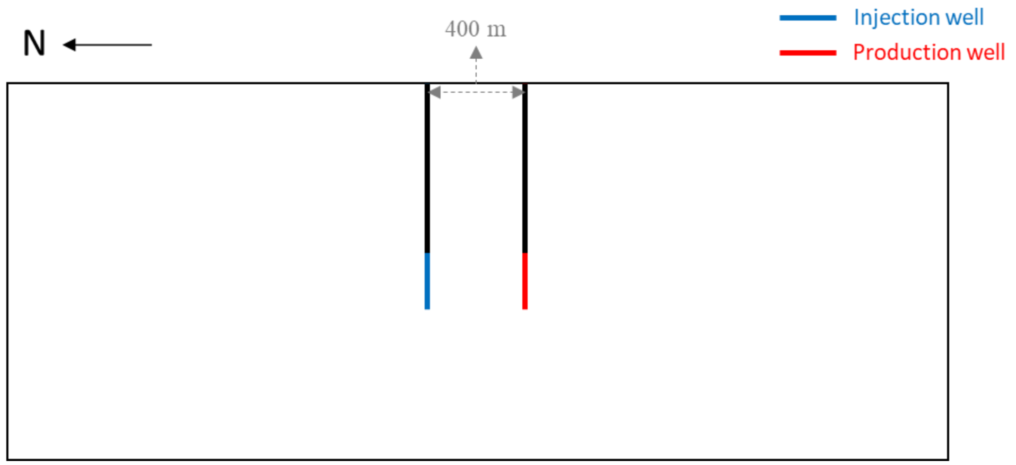
- In future work, based on the results of this study, a more careful parameter setup for the numerical model will be conducted, and different scenarios of water extraction will be designed to understand the impact of different scenarios on the production well productivity in the thermo-hydro-mechanical coupled model.

Scenarios

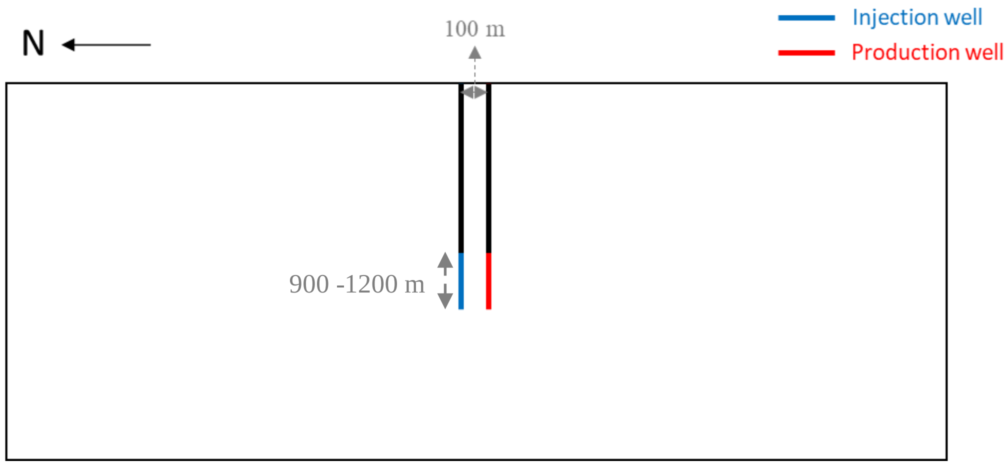

N
100 m
Injection well
Production well

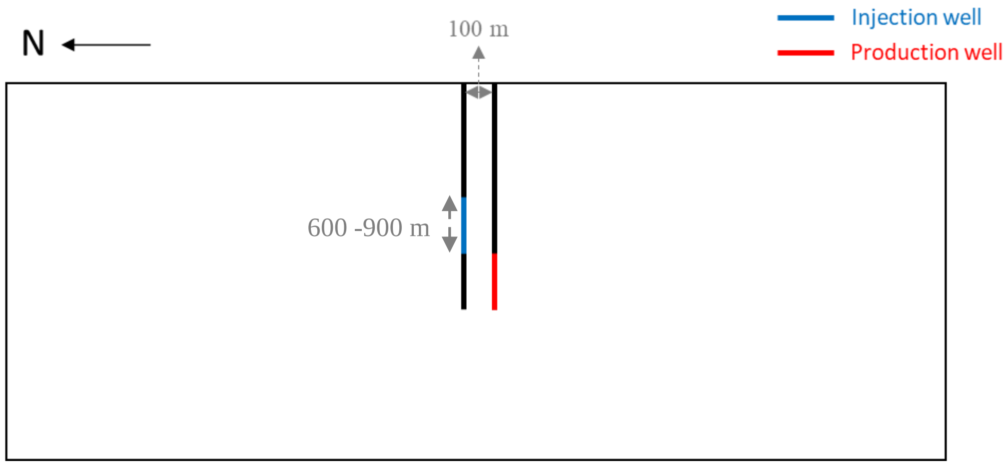

N
200 m
Injection well
Production well

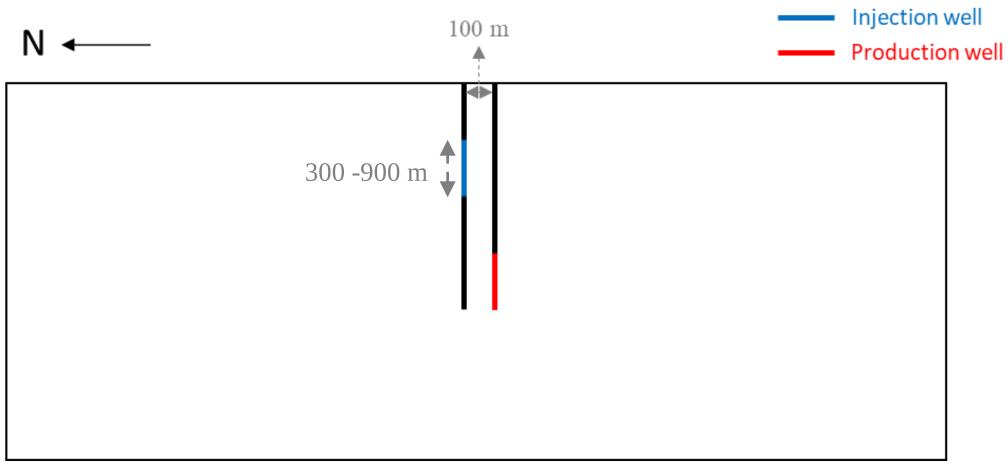

N
300 m
Injection well
Production well


N
400 m
Injection well
Production well

Scenarios


N
100 m
Injection well
Production well
900 -1200 m


N
100 m
Injection well
Production well
600 -900 m


N
100 m
Injection well
Production well
300 -900 m

Thank you for listening