SMART Initiative - Phase 2

Science-informed Machine Learning to Accelerate Real Time (SMART) Decisions in Subsurface Applications

ML-Based Optimization for CO_2 Injection under Geomechanical Risks

Bailian Chen, Fangning Zheng, Martin Ma

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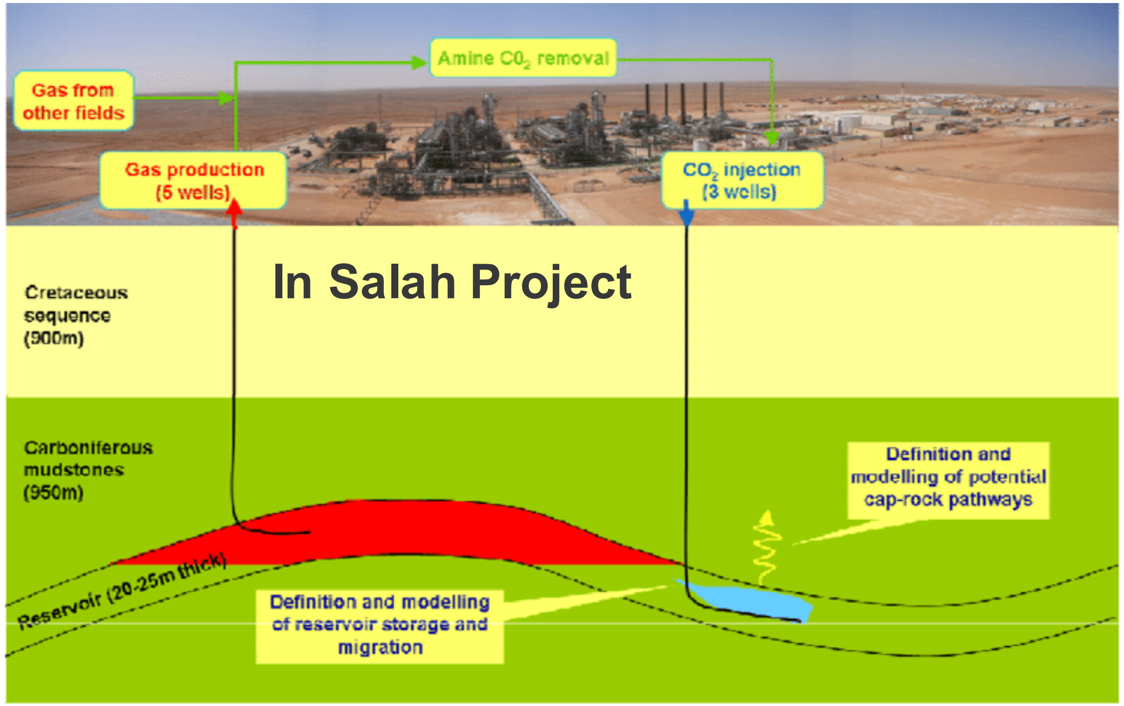
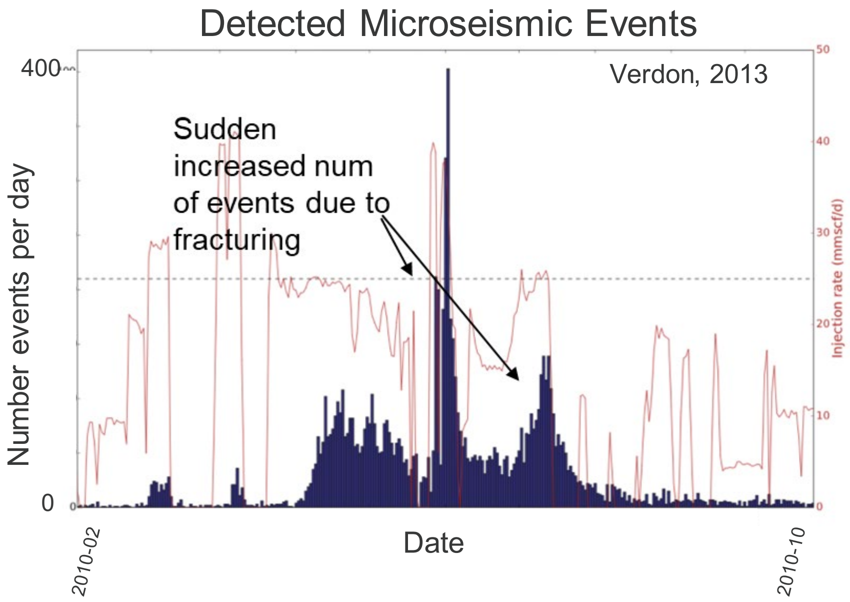
NATIONAL ENERGY TECHNOLOGY LABORATORY

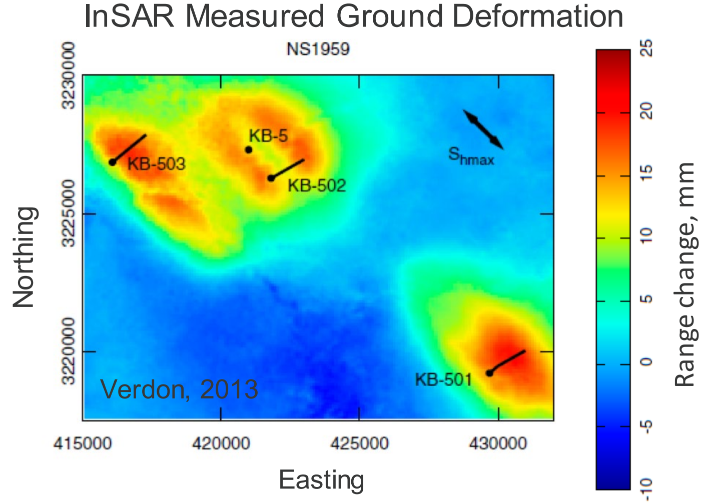
U.S. DEPARTMENT OF ENERGY

Motivation



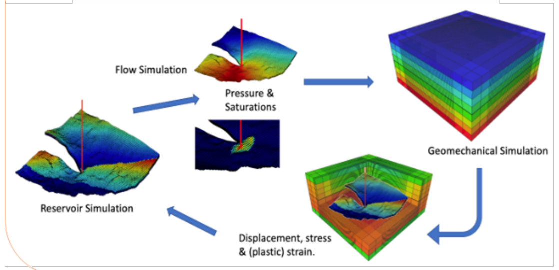
- A total of **3.8 mega-ton** of CO_2 were injected
- **9,506** micro-seismic events detected during injection
- Maximum of **25 millimeters uplift**





Motivation

Coupled Flow-Geomechanics Model



Governing Equations

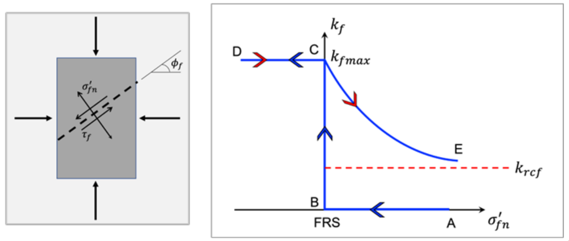
- Fluid Mass Balance:

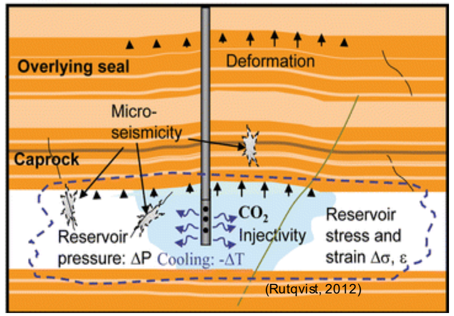
$$\frac{dm_\beta}{dt} + \nabla \cdot w_\beta = \rho_\beta f_\beta$$

- Linear Momentum Balance:

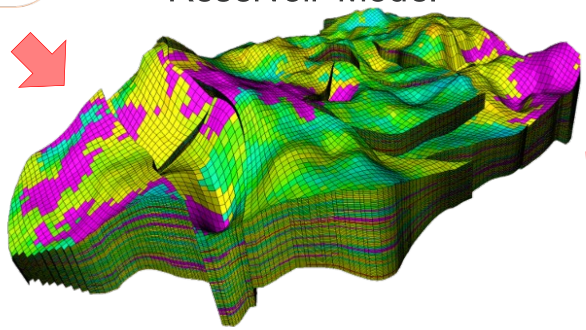
$$\nabla \cdot \sigma + \rho_b g = 0$$

Barton-Bandis Fracturing Model

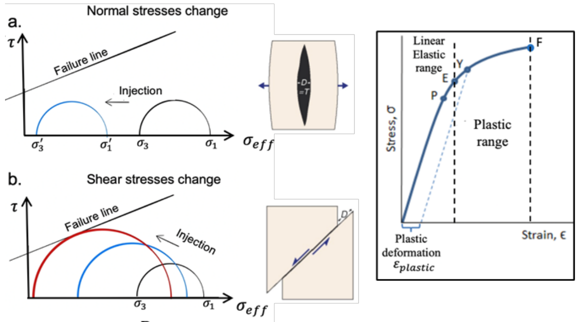




Reservoir Model

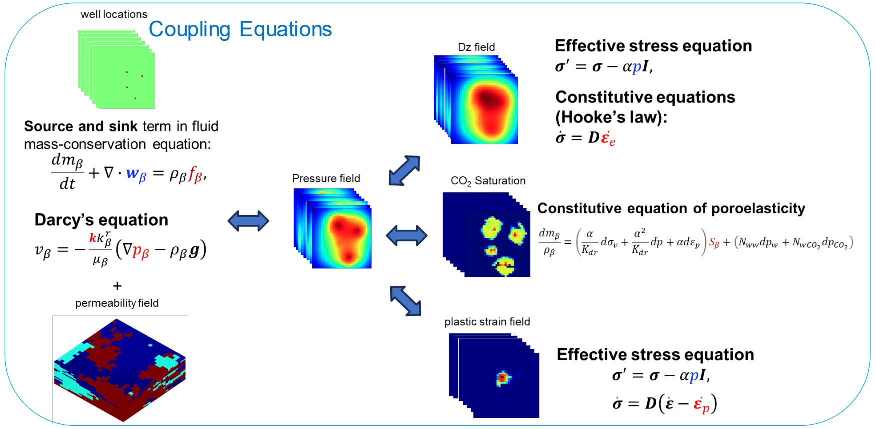


Mohr-Coulomb's Failure Criterion



$$\sigma_{total} = \alpha P_p + \sigma_{eff}$$

Coupling Equations



Computationally Demanding !!!

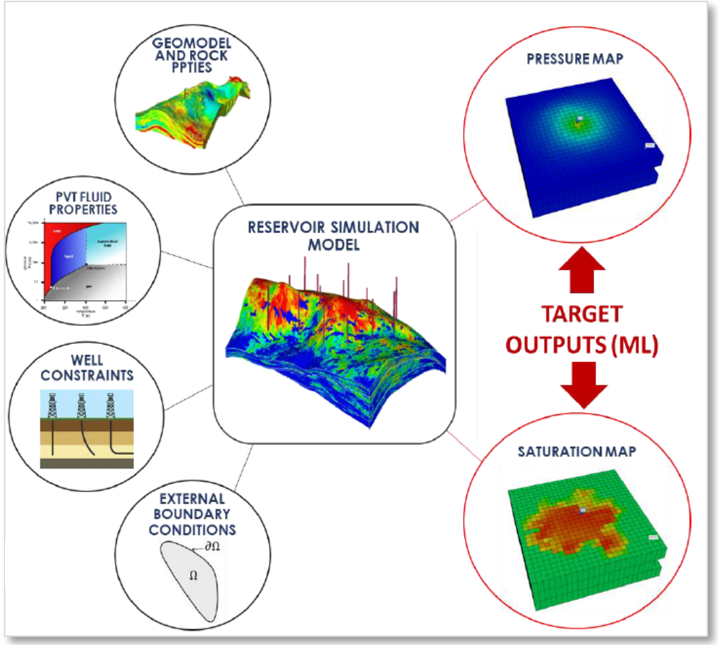
Introduction

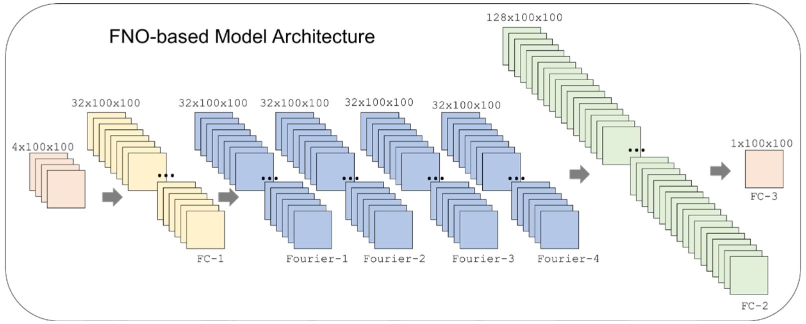
Main Objective:

Develop a ML-assisted optimization workflow to optimize CO_2 storage performance under Geomechanical risks.

Major Components of Workflow:

1. Construct a physics-based CO_2 storage model and quantify the associated geomechanical risks, including ground displacement and safety factor.
2. Develop a ML-based surrogate model to output the quantified geomechanical risks.
3. Build an optimization workflow to optimization CO_2 storage while minimizing geomechanical risks.

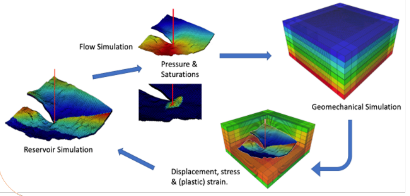




Methodology – Physics-based Model

Build a coupled flow-geomechanics simulation model for CO_2 storage

Coupled Flow-Geomechanics Model



Governing Equations

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$$\frac{dm_\beta}{dt} + \nabla \cdot w_\beta = \rho_\beta f_\beta$$

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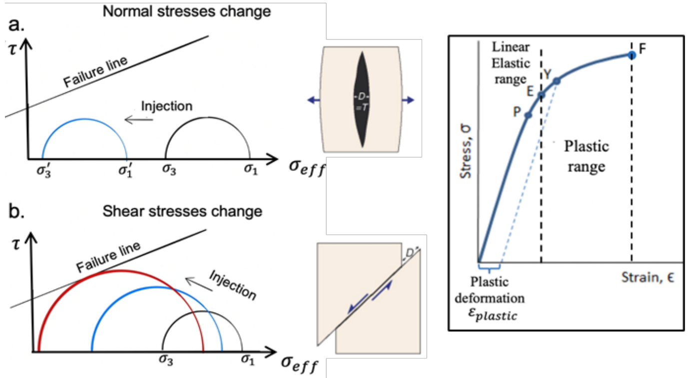
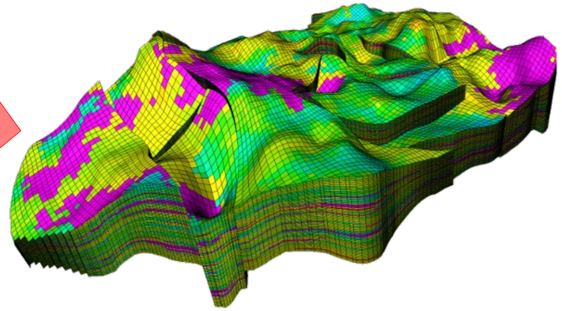
Mohr-Coulomb's Failure Criterion

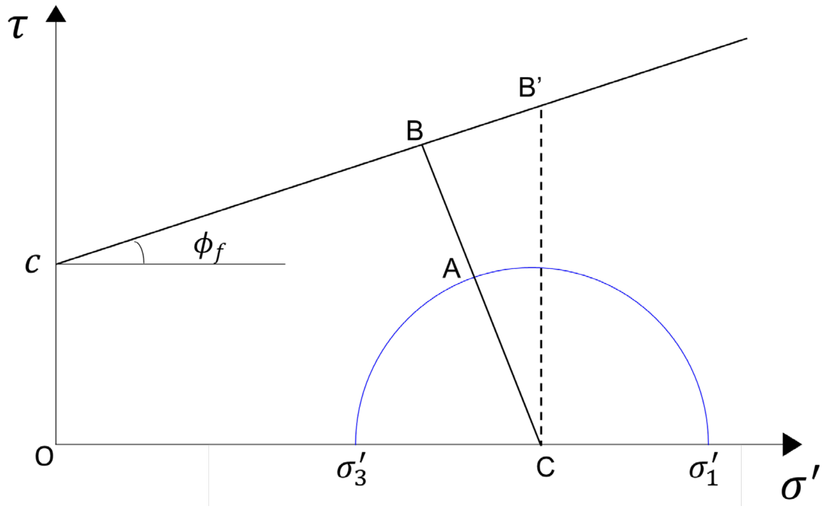


$$\sigma_{total} = \alpha P_p + \sigma_{eff}$$

Reservoir Model



Safety Factor (potential to trigger micro-seismicity)

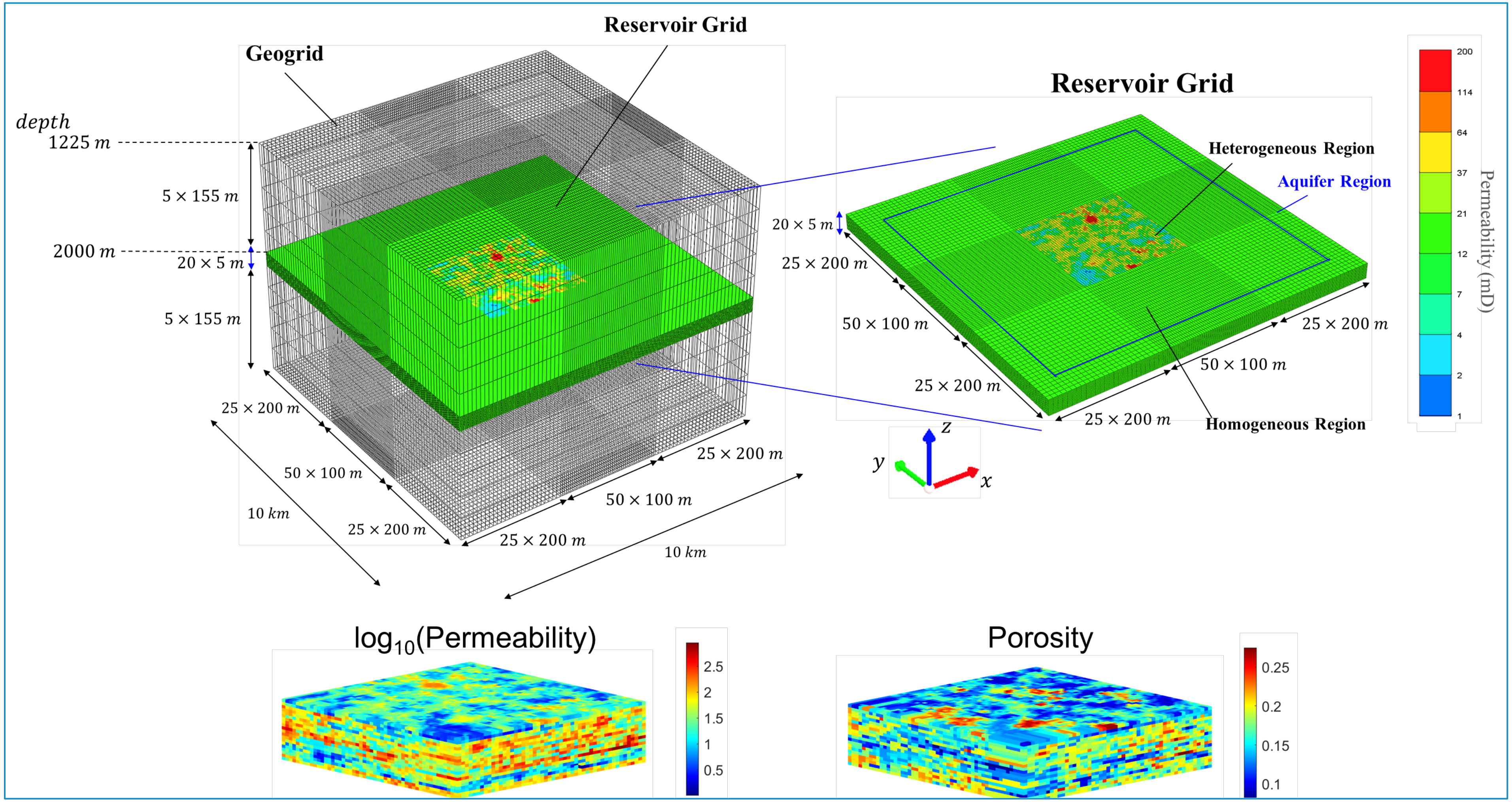


$$SF = 1 - (\min(1, CA/CB))$$

Large SF → safer injection
Small SF → dangerous
SF = 0 → Rock failure

Methodology – Physics-based Model

Build a coupled flow-geomechanics simulation model for CO_2 storage



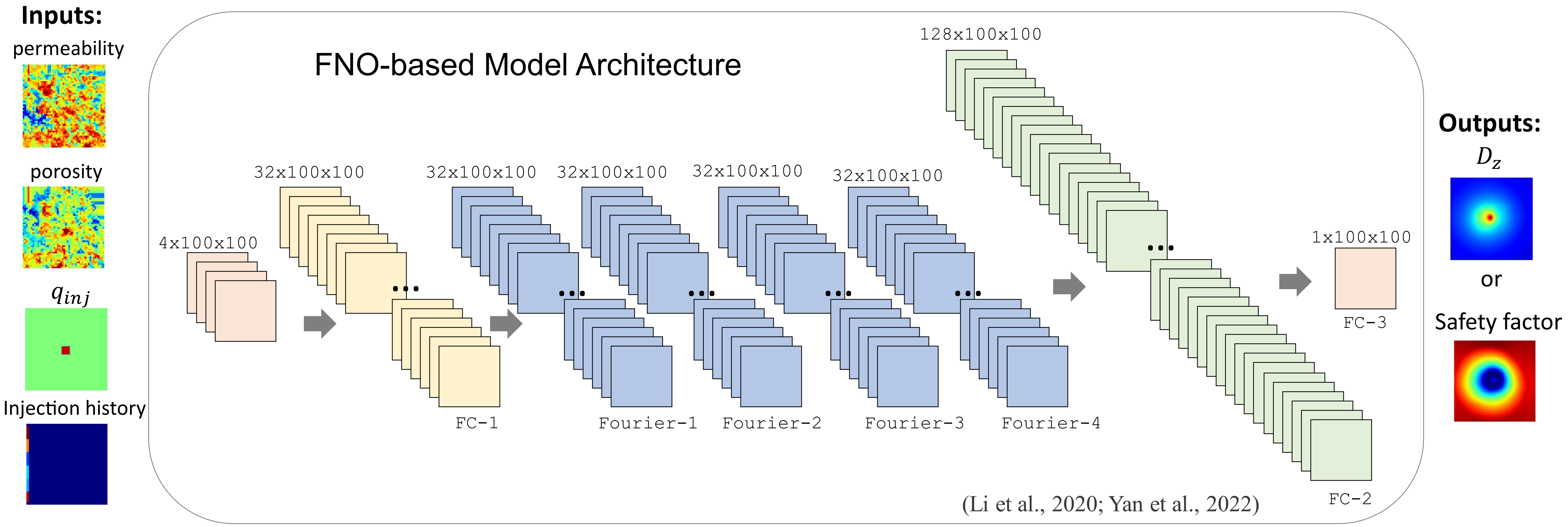
Methodology – Physics-based Model

Model Settings

		Base case	Low permeability case
Flow properties	Permeability (mD)	**0.69 - 936.90**	**0.069 – 93.69**
	Porosity	0.078 - 0.27	same
	Reservoir depth (m)	2000 - 2050	
	pore pressure gradient (kPa/m)	9.8	
	Temperature (C)	44	
	Kv/kh	0.1	
Geomechanical Properties	Young's Modulus (GPa)	45	
	Poisson's Ratio	0.25	
	Cohesion (kPa)	3000	
	Friction Angle	20	
	Biot's coefficient	0.8	
	$\partial\sigma'_{xx}/\partial z$ (kPa/m)	10	
	$\partial\sigma'_{yy}/\partial z$	12	
	$\partial\sigma'_{zz}/\partial z$	13	

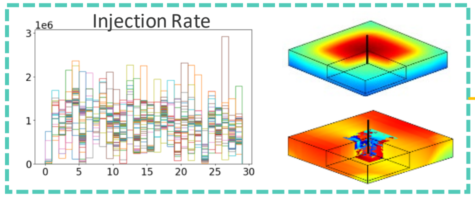
Methodology – ML-based Model

Construct an FNO-based surrogate model using synthetic dataset



Methodology – General Optimization Workflow

Synthetic Dataset

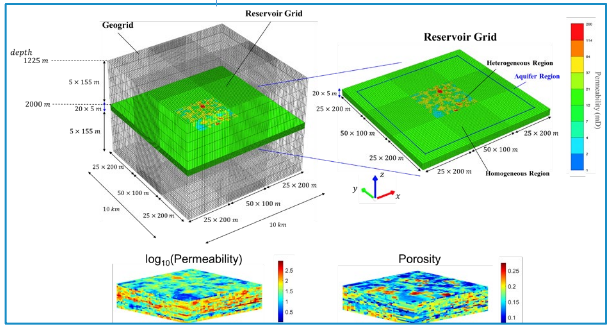


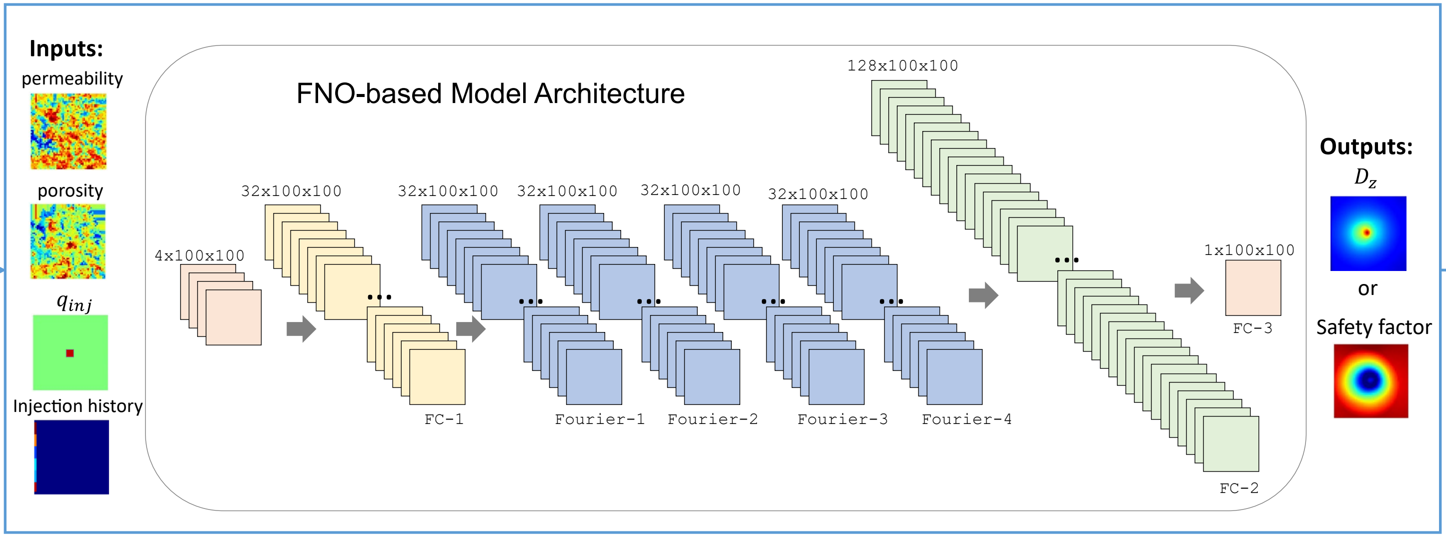
$$f(\boldsymbol{u})\begin{cases} f_1 = \max(M_{CO_2}(\boldsymbol{u})), \\ f_2 = \min(\max(D_z)), \\ f_3 = \max(\min(safty\ factor)). \end{cases}$$

$$subject\ to \quad \begin{matrix} M_{CO_2\_min} \leq M_{CO_2}(\boldsymbol{u}), \\ M_{CO_2}(\boldsymbol{u}) \leq M_{CO_2\_max}. \end{matrix}$$

Genetic Algorithm

Build physics-based model → Develop proxy model → Define decision variables and objective function → Select optimization algorithm → Determine the optimal control parameters





Result – Base Case

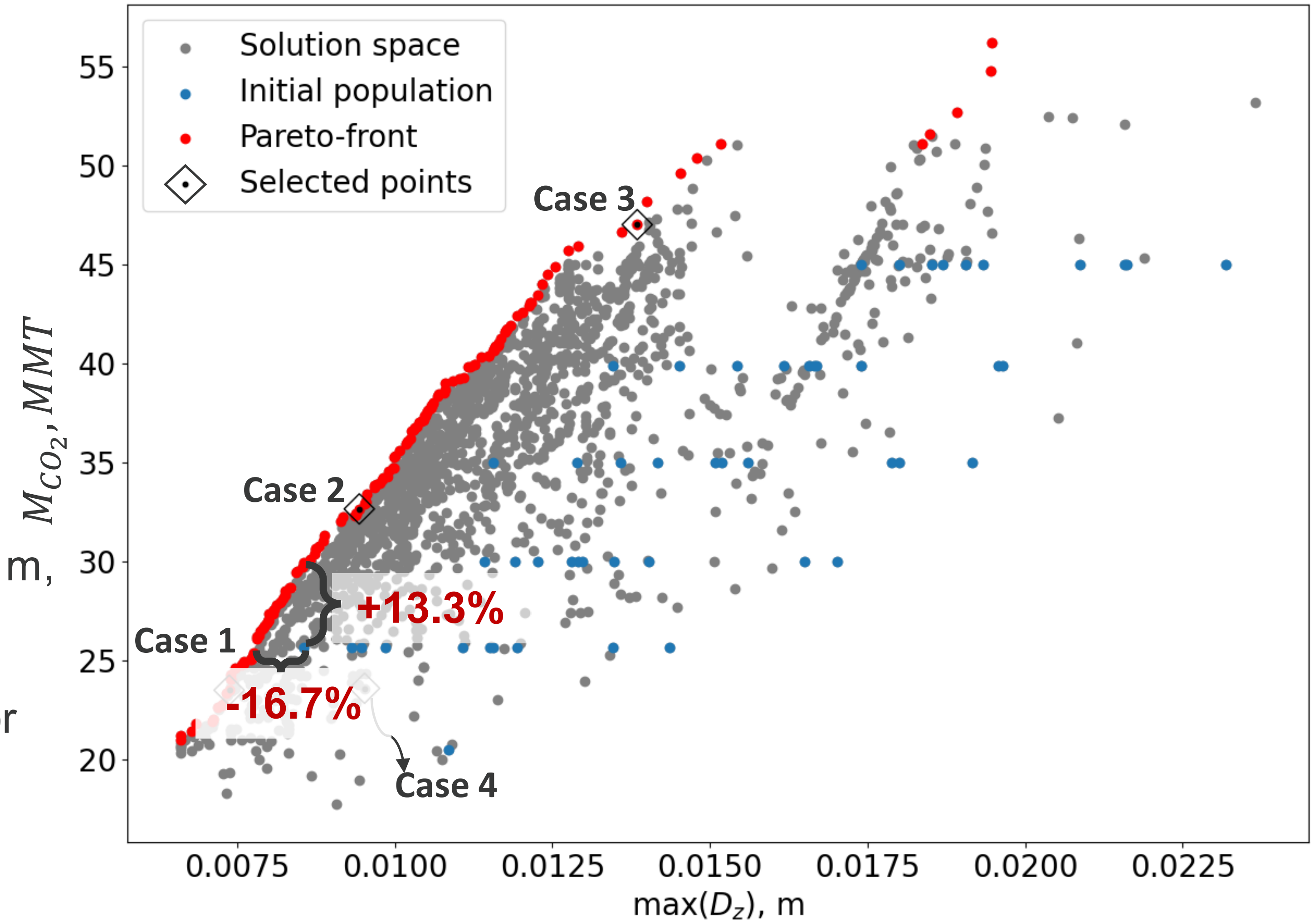
Bi-objective Optimization:

$$\boldsymbol{u}^* = argmin_{u \in \emptyset_u} \boldsymbol{f}(\boldsymbol{u}) = \begin{cases} f_1(\boldsymbol{u}) = max(M_{CO_2}(\boldsymbol{u})), \\ f_2(\boldsymbol{u}) = min(max(\boldsymbol{D_z}(\boldsymbol{u}))). \end{cases}$$

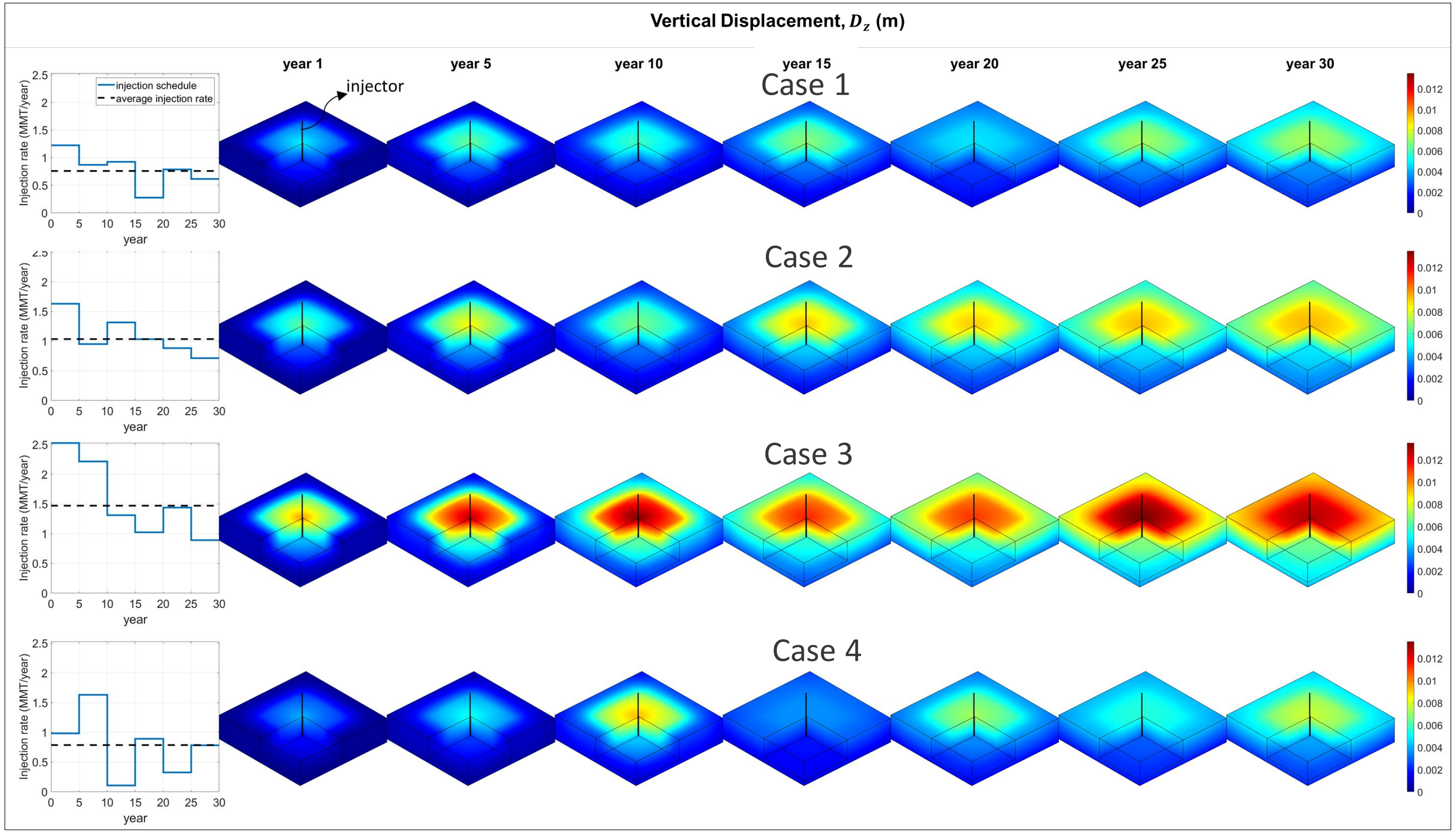
$$subject\ to \quad \begin{matrix} M_{CO_2\_min} \leq M_{CO_2}(\boldsymbol{u}), \\ M_{CO_2}(\boldsymbol{u}) \leq M_{CO_2\_max}. \end{matrix}$$

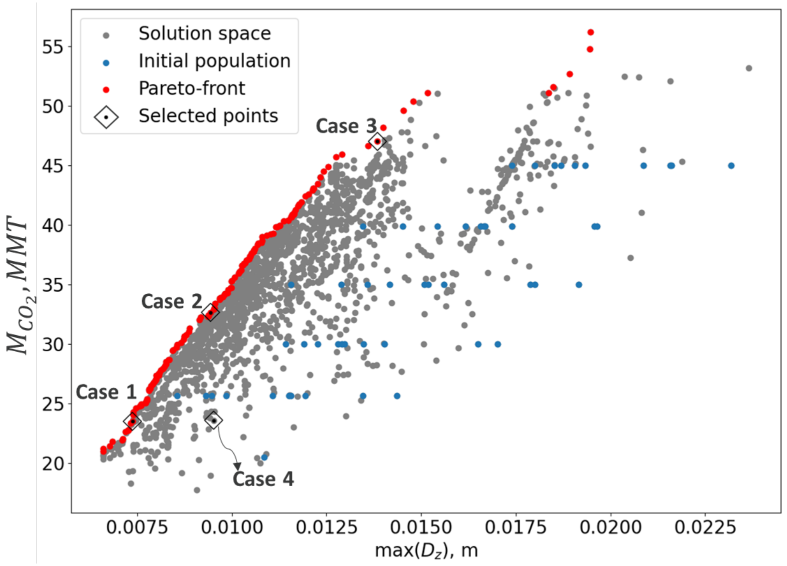
- Optimization minimizes optimal vertical displacement from initial of 0.009 to 0.0075 m, achieving **16.7% mitigation**.
- **Increase** optimal CO_2 **storage** for **13.3%** for same level of displacement.

GA Optimization Results



Result – Base Case





- As total storage increase, maximum vertical displacement also increases. (Cases 1, 2, 3)
- The **maximum injection rate** for Pareto solutions occur at the **beginning** of the injection period where reservoir has more room for pressure buildup, resulting in **less** vertical displacement. (Case 1 vs Case 4)

Result – Low Permeability Case

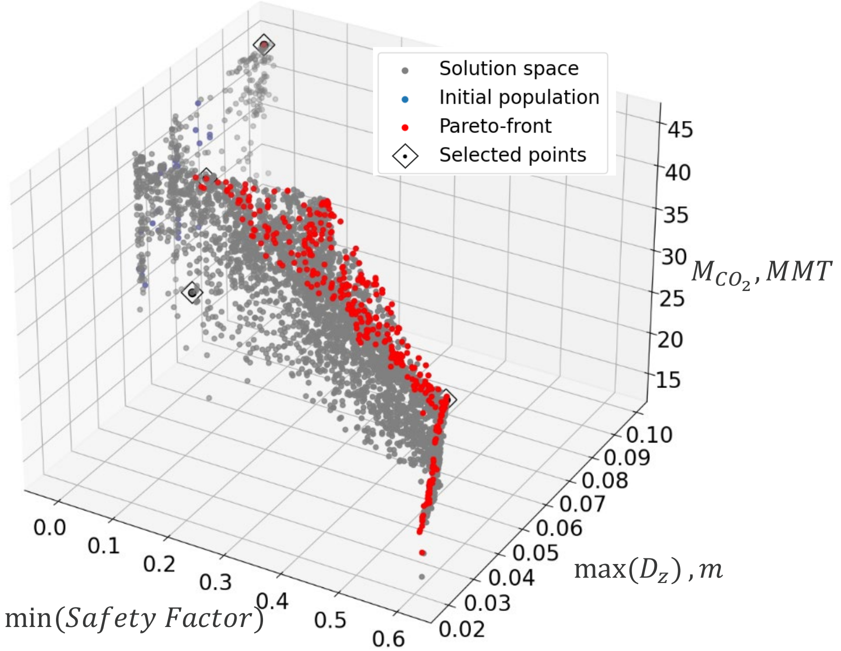
Optimization Formulation:

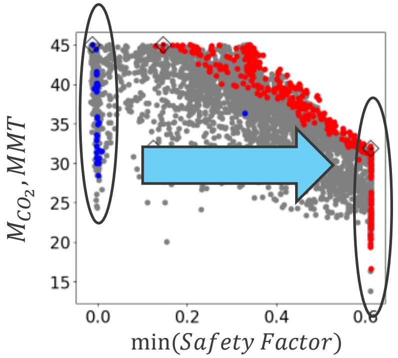
$$
\boldsymbol{f}(\boldsymbol{u}) \begin{cases} f_1 = \max(M_{CO_2}(\boldsymbol{u})), \\ f_2 = \min(\max(D_z)), \\ f_3 = \max(\min(safty\ factor)). \end{cases}
$$

$$
subject\ to \quad M_{CO_2\_min} \leq M_{CO_2}(\boldsymbol{u}), \quad M_{CO_2}(\boldsymbol{u}) \leq M_{CO_2\_max}.
$$

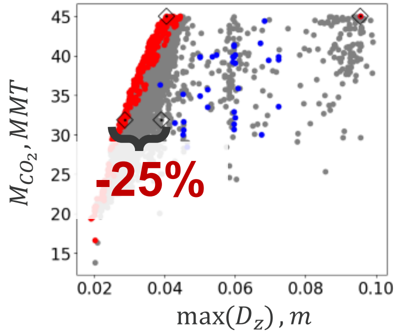
- The optimization algorithm successfully **improves** the initial population's minimum safety factor from **0** **(indicating rock fracturing)** to a Pareto population maximum value of **0.61** **(indicating safe injection)**.
- The optimal maximum vertical displacement also **decreased** from approximately **0.04 m** to about **0.03 m**, achieving **25% mitigation**.
- An **early maximum injection** allowed for **better pressure dissipation**, leading to **safer storage** (consistent with previous observation).

GA Optimization Results

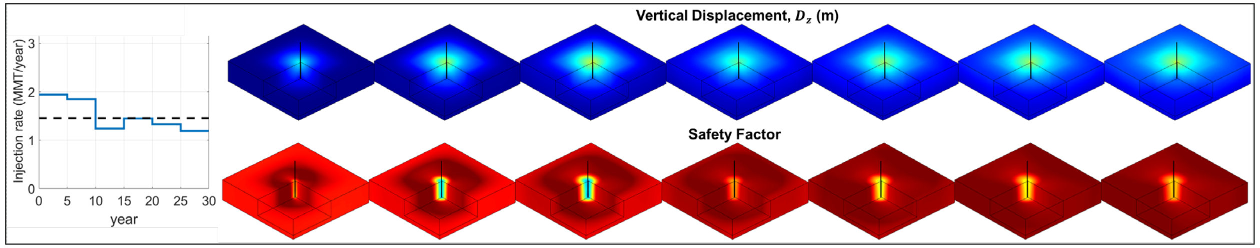




Case 1

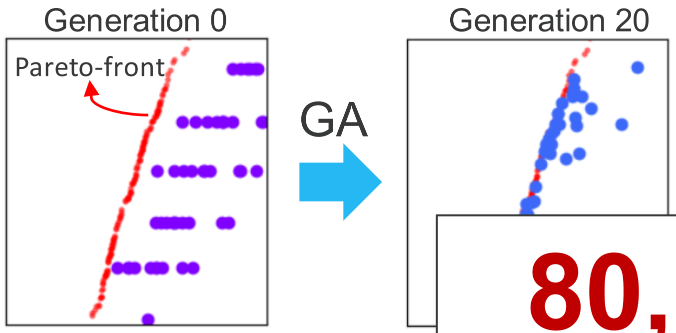


Case 1

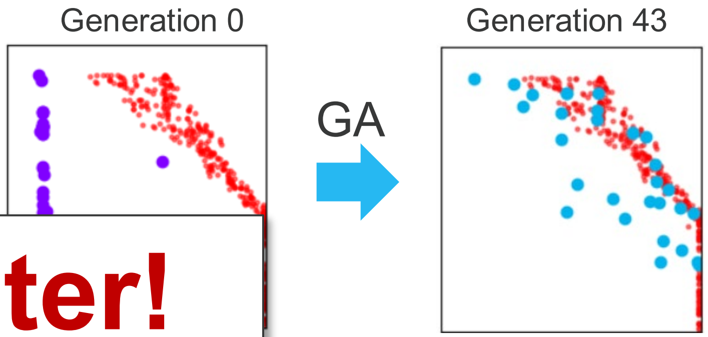


Result – Computational Cost

Base Case



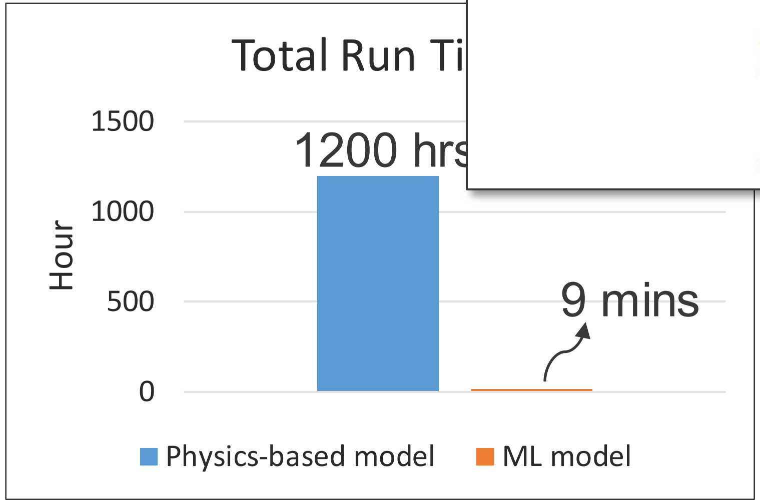
Low Perm Case

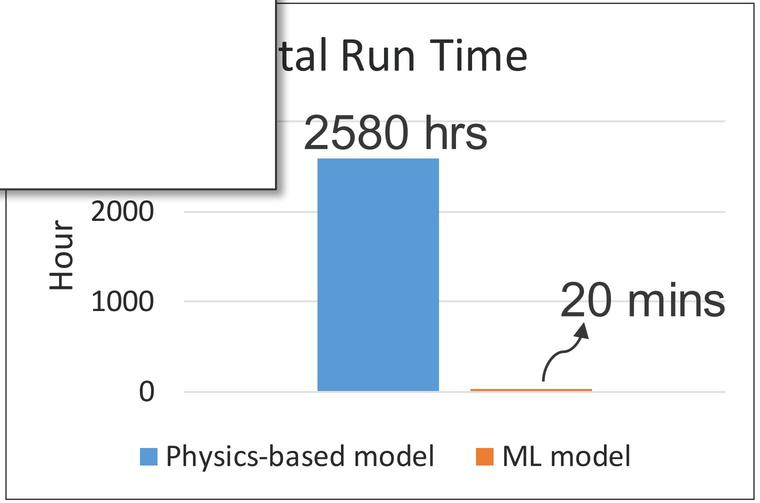


# of simulation evalu

ation evaluated: 1290

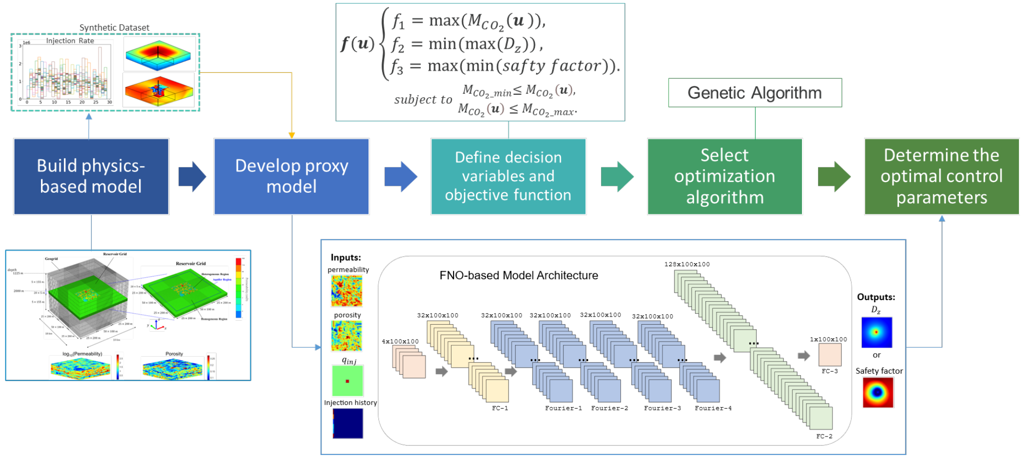
80,000 times faster!



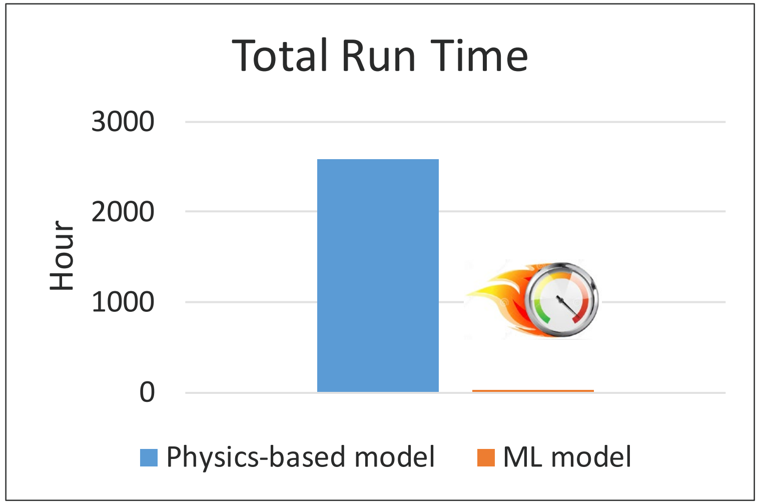


Summary

- Challenging problem – CO_2 Storage under Geomechanics:
  - Non-linear and Multiphysics Processes
  - Complex Rock's Failure/Fracturing Mechanisms
  - Non-convex, Global Optimization Formulation
  - High Computational Cost



- Demonstrated the effectiveness of using FNO-based ML-surrogate models and the NSGA-II Genetic Algorithm for optimizing CO_2 injection strategies under geomechanical risks.
- The Pareto-front indicates optimal **trade-offs** between CO_2 storage, safety (micro-seismicity), and vertical displacement.
- Achieved **80,000-fold computational cost saving**.



Thank you!