Extending TOUGH+HYDRATE with a Parallel Particle Transport Simulator: Numerical Investigation of Sand Production Issues During Production from Hydrate Deposits

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U.S. Department of Energy

National Energy Technology Laboratory

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Presentation Outline

- Task Motivations and Objectives
- Parallel Tough + Hydrate + Particle Transport (THPT) Simulator
- Representative Accomplishments
- Task Challenges

Task Motivation

❑ Abrupt termination of hydrate production trials

- Clogging of pore throats
- Blockage of the well head
- Equipment failures

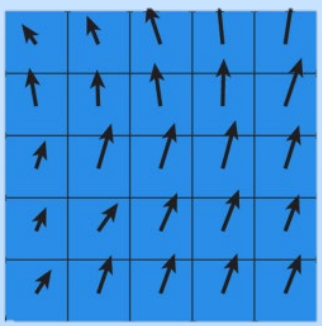
Sand production, North Slope of Alaska (Schoderbek et al., 2013)

Sand production, Nankai Trough (Yamamoto et al., 2017)

Task Motivation

❑ Few simulations based on Lagrangian Method

Eulerian		vs Lagrangian
Continuum approach	•	Discrete element approach
Geomechanics/Concentration	•	Geomechanics+Particle tracking
Low computational cost	•	High computational cost
Uchida et al (2016), Yan et al (2018), Loret et al (2019), Akaki et al (2020), Li et al (2024), …	•	Kazidenov et al (2023)



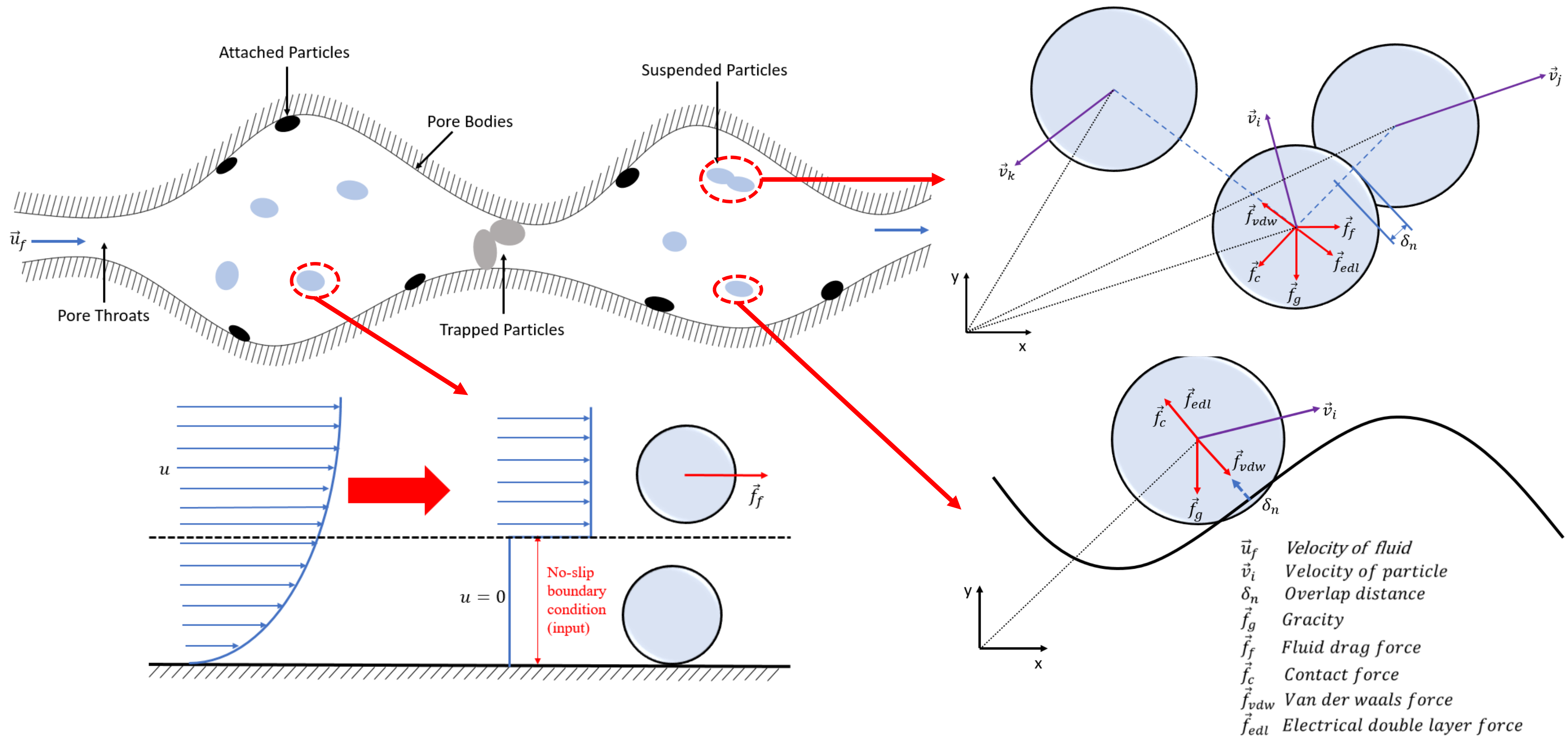
Task Objectives

- To develop a parallel Tough + Hydrate +Particle Transport (THPT) code capable of standalone application or seamless integration with TOUGH+HYDRATE
- To leverage the Lagrangian Discrete Element Method (DEM) to simulate the discrete characteristics inherent in sand production issues

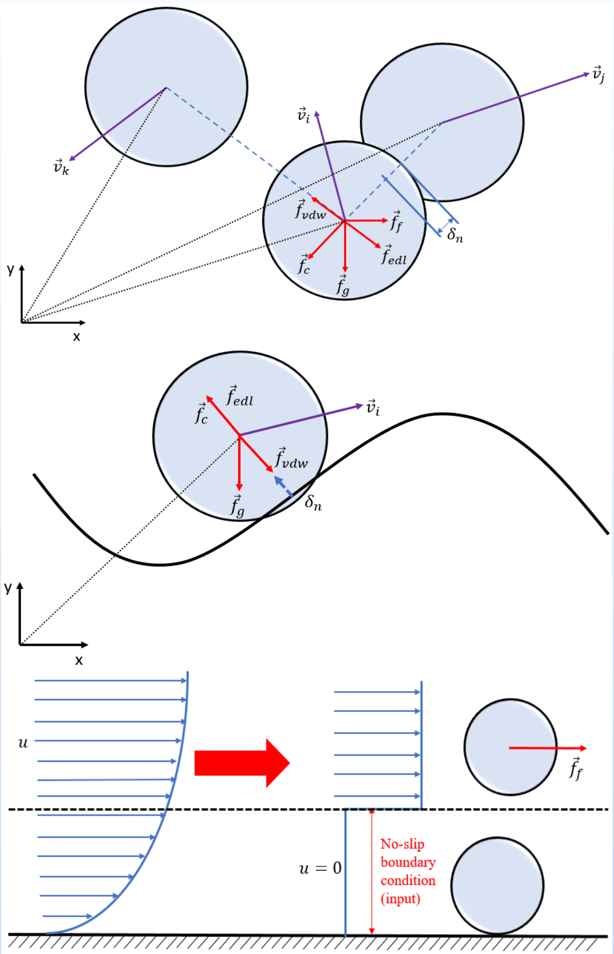
THPT: Simulation Approach - DEM

DEM Governing Equations

Force → Acceleration → Velocity → Position



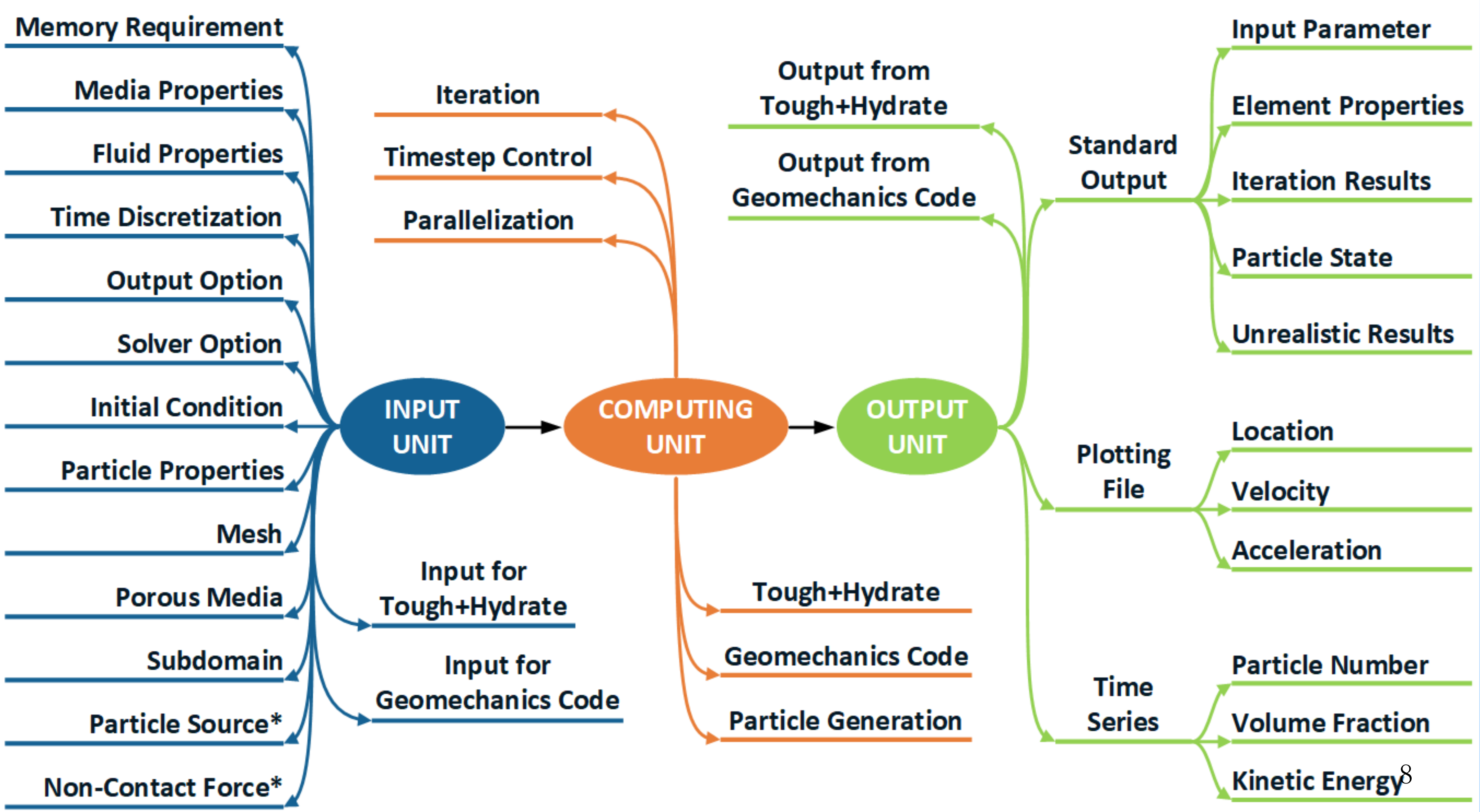
THPT: Underlying Physical Models



Forces	Symbol	Equations
Elastic force	f_{ij}^{cn}	$-\frac{4}{3}E^*\sqrt{R^*}\delta_n^{\frac{3}{2}}\mathrm{n}$
Damping force	f_{ij}^{dn}	$-c_n\left(8m_{ij}E^*\sqrt{R^*\delta_n}\right)^{\frac{1}{2}}v_{\mathrm{n},ij}$
Van der Waals force	f_{ij}^{wdl}	$f_{vdw}=\frac{A_H}{24d}\left(\frac{1}{x^2}\right)\vec{n}_{ij}$
Electrical double layer force	f_{ij}^{edl}	$4\pi\epsilon(z\psi)^2\mathrm{Rexp}(-\kappa\mathrm{d})$
Drag force(*)	$f_{\mathrm{f},i}$	$C_d\varepsilon_f\frac{\pi\left(D_p\right)^2}{4}\frac{\rho_f(\mathrm{u}-v)^2}{2}\varepsilon_f{}^{-\chi}$
Gravity	$f_{\mathrm{g},i}$	$m_i\mathrm{g}\left(1-\frac{\rho_f}{\rho_p}\right)$
$(*)\chi=3.7-0.65\exp\left[-\frac{(1.5-log(Re))^2}{2}\right],\ C_d=\left(0.63+\frac{4.8}{Re_p^{0.5}}\right)^2$		

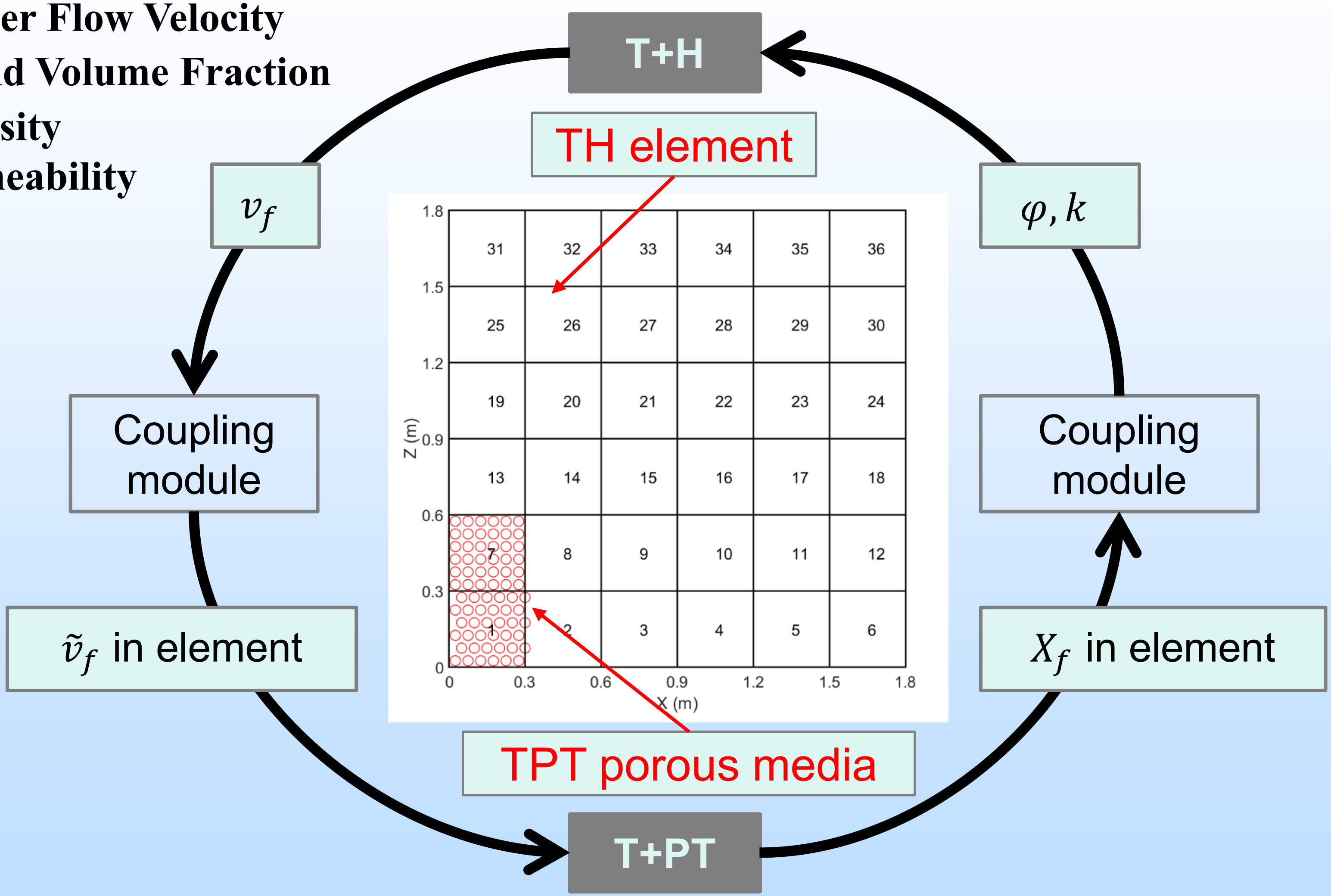
THPT: Architecture

Fortran 95/03



THPT: Coupling Scheme

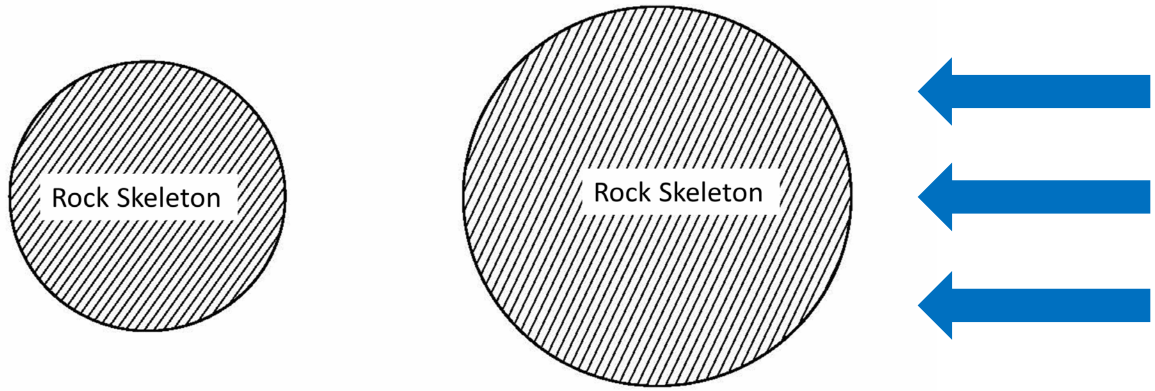
v_f: Water Flow Velocity
X_f: Fluid Volume Fraction
φ: Porosity
k: Permeability



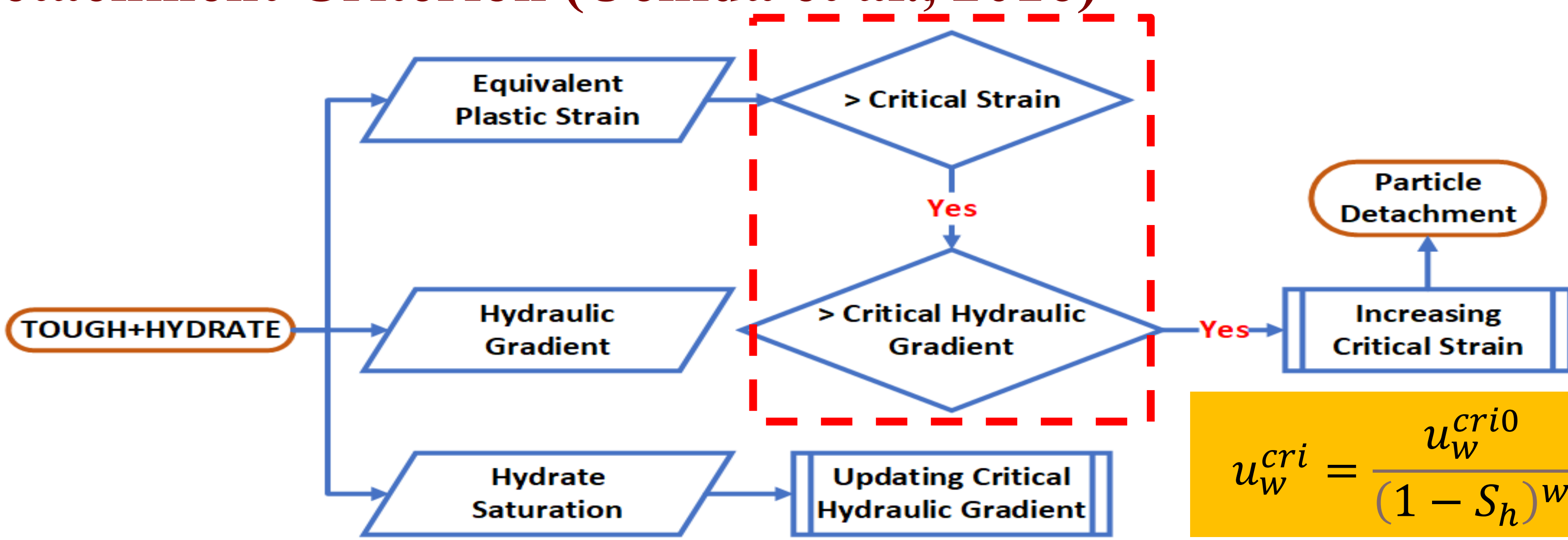
Assuming that the presence of particles does not change the fluid properties

THPT: Particles Detachment

Rock skeleton: Cementation of sand grains and hydrate



Detachment Criterion (Uchida et al., 2016)

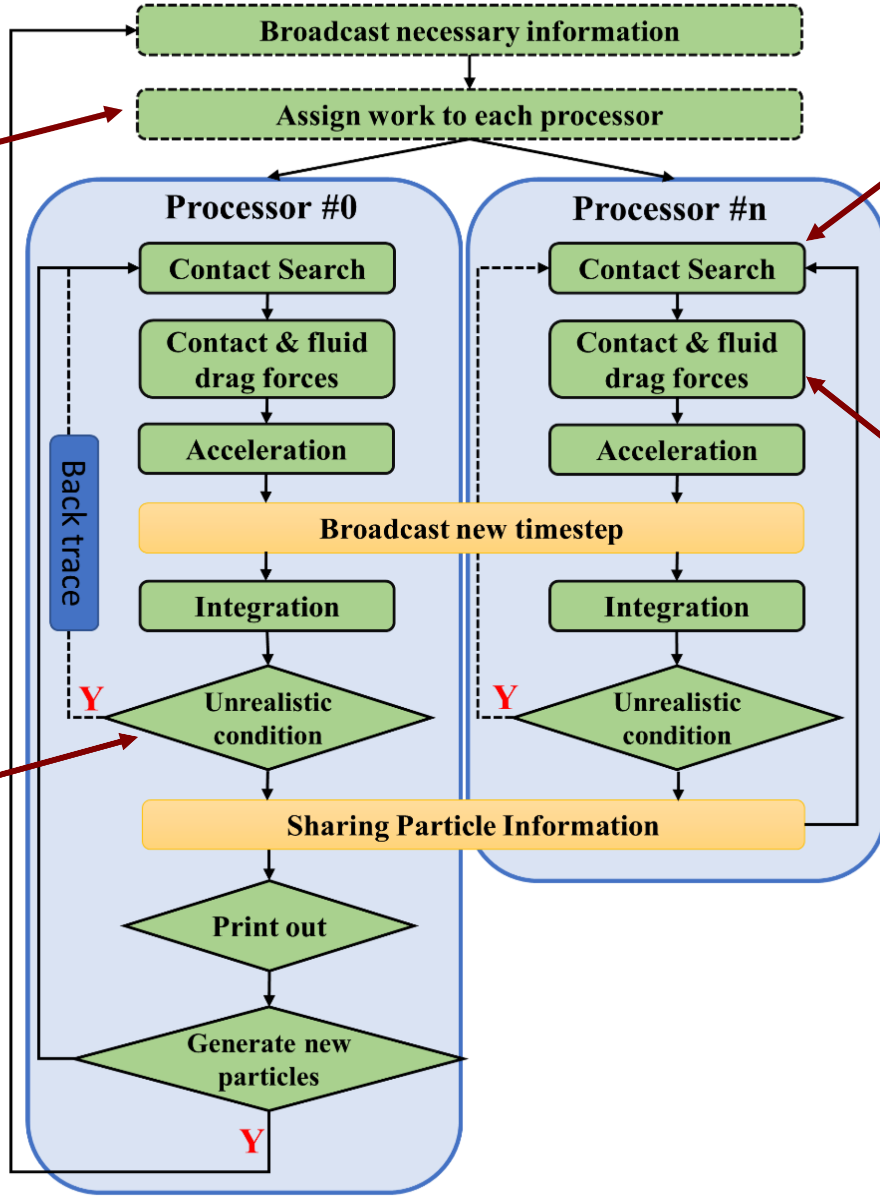


$$u_w^{cri} = \frac{u_w^{cri0}}{(1 - S_h)^w}$$

THPT: Improve Computing Efficiency

Parallelization

Automatic Timestep Control

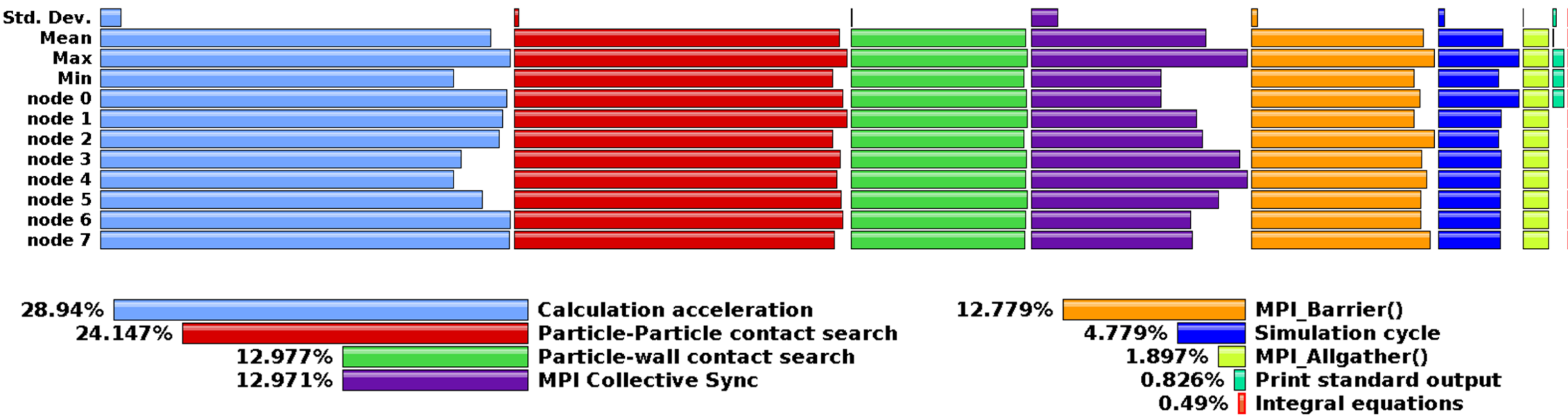


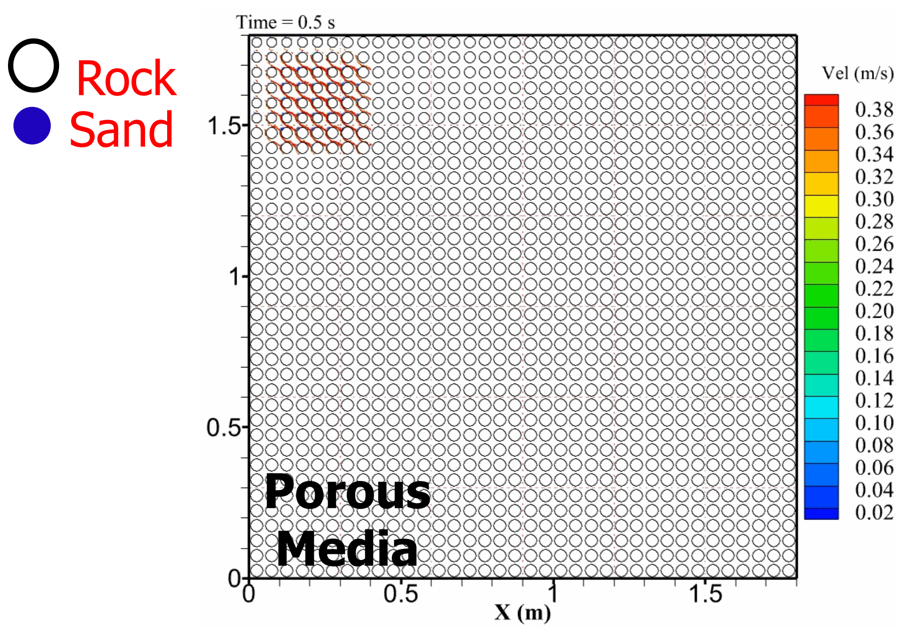
Highly efficient algorithm

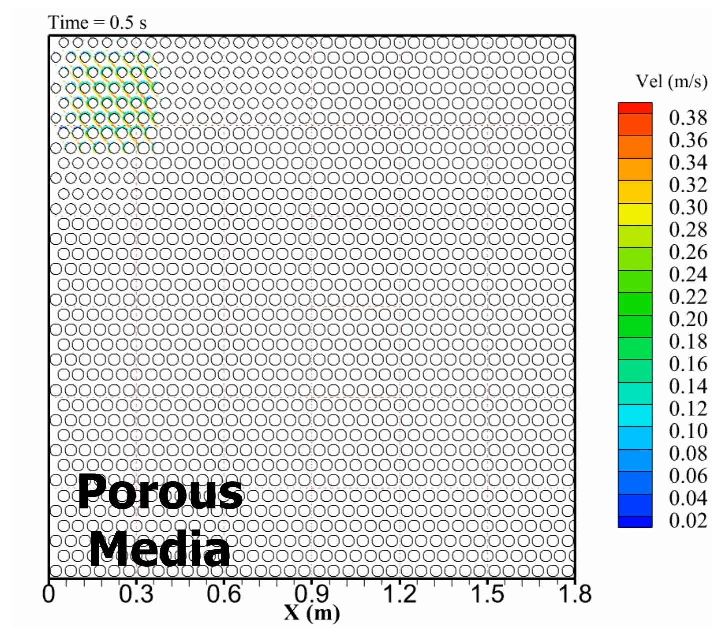
Ignore minor forces

THPT: Parallel Performance

Balanced workload on each node

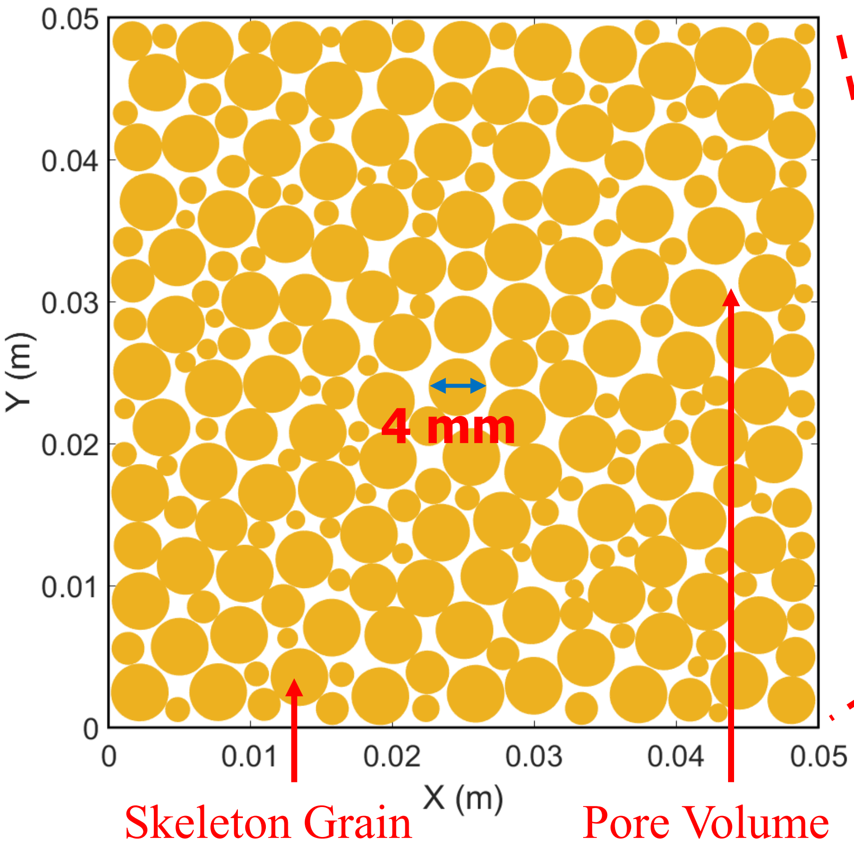




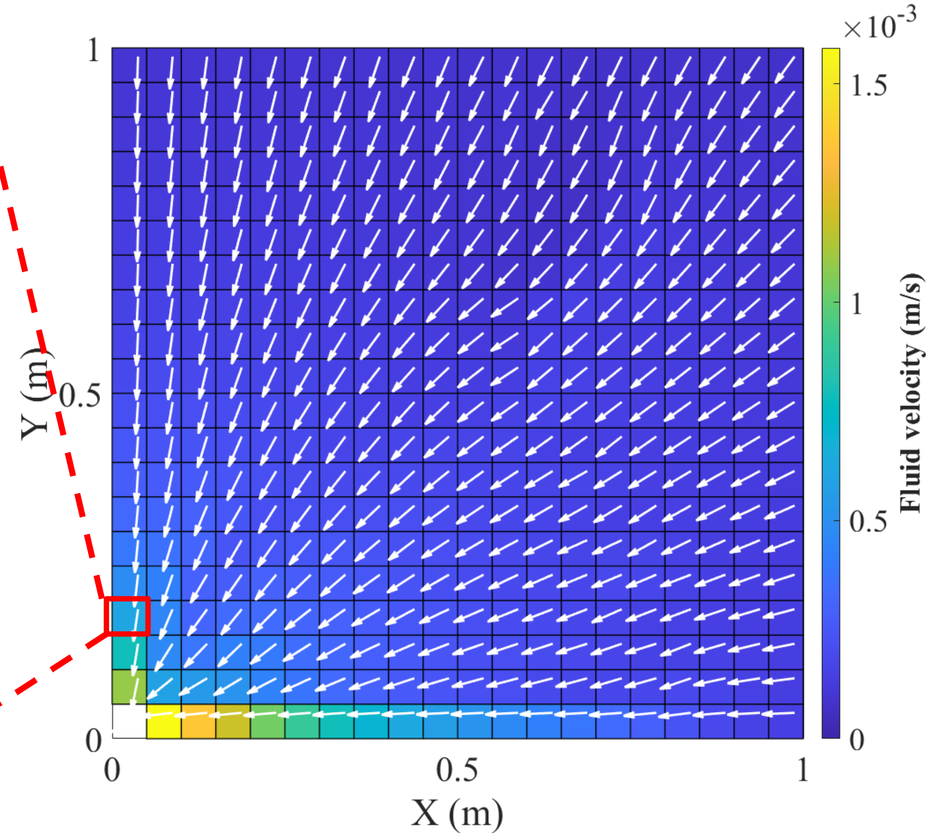


Representative Accomplishments

Porous Media in TPT



Mesh in TH



Skeleton grain number: **273**
Maximum grain size: **4 mm**
Minimum grain size: **0.6 mm**

Simulation domain size: **10 m × 10 m**
Element size: **0.05 m × 0.05 m**
Element number: **40000**

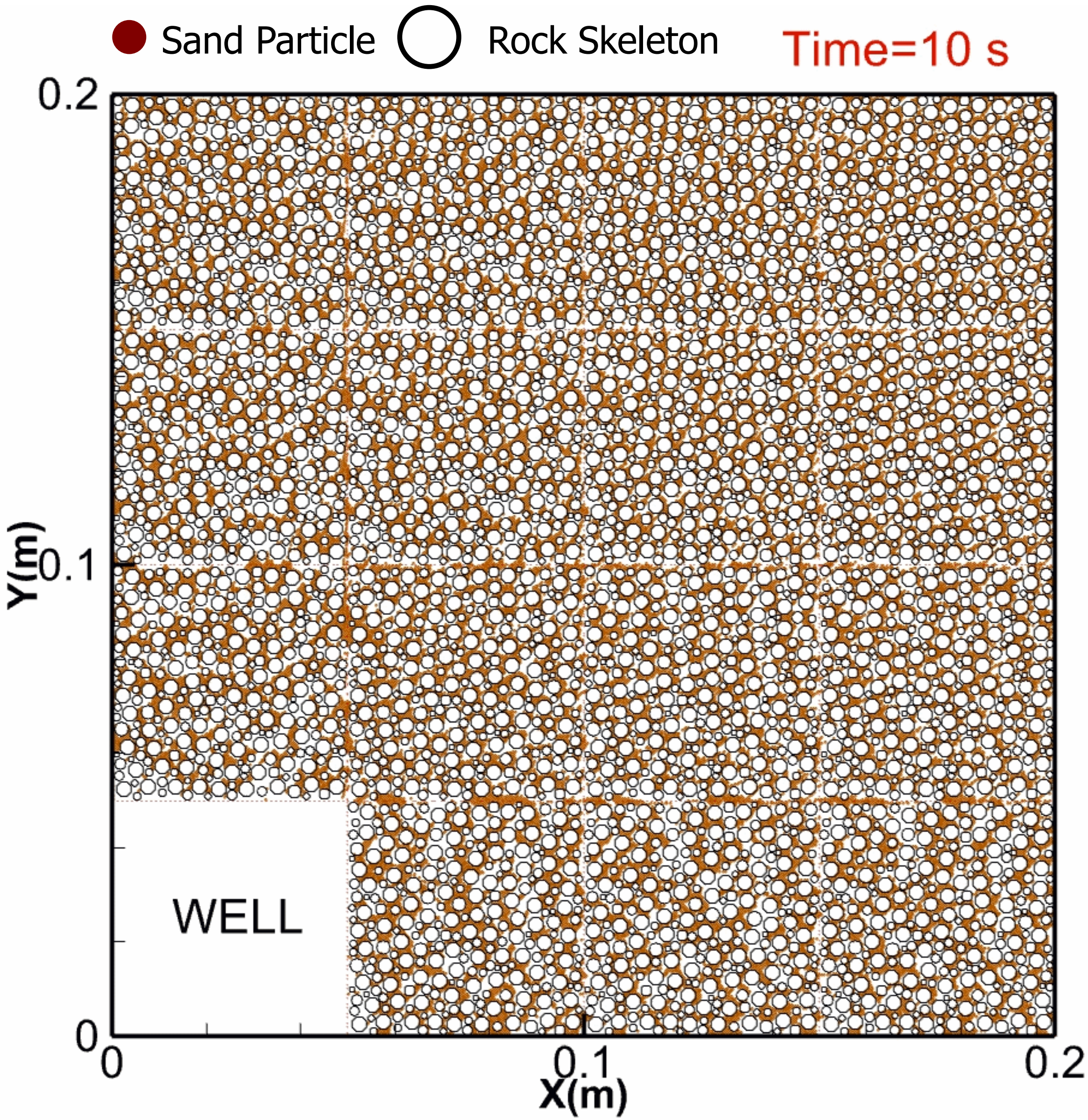
Modeling Settings

Parameter	Value
Rock density	2600 Kg/m³
Initial porosity	0.3
Intrinsic Perm	2.96×10^{-13}
Hydrate density	920 kg/m³
Initial pressure	13 MPa
Initial temperature	288 K
Initial hydrate saturation	0.5
Initial water saturation	0.5
Irreducible water saturation	0.12
Entry capillary pressure	0.125 MPa
Relative permeability model	$k_{rA} = \max\left\{0, min\left\{\left[\frac{S_A - S_{irA}}{1-S_{irA}}\right]^n, 1\right\}\right\}$ $k_{rG} = \max\left\{0, \min\left\{\left[\frac{S_G - S_{irG}}{1-S_{irA}}\right]^n, 1\right\}\right\}$
Capillary pressure	

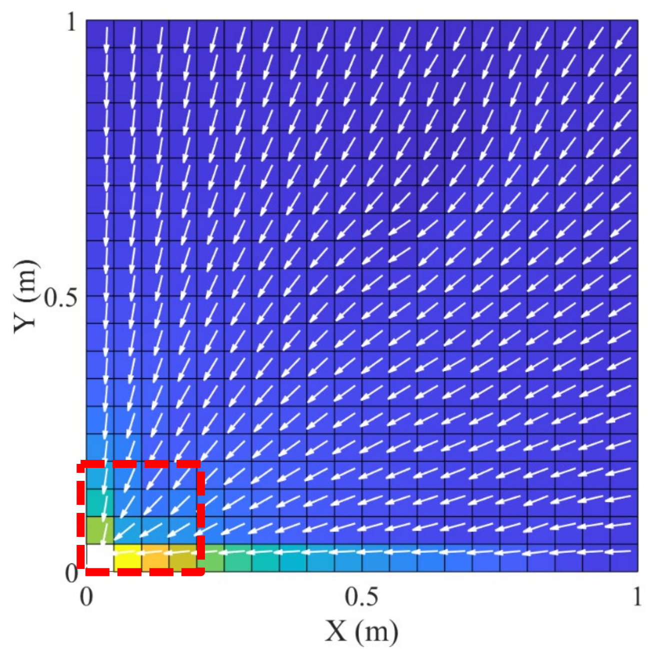
Parameter	Value
Rock young modulus	1.0 MPa*
Poisson ratio	0.3
Damping coefficient	0.3
Sand particle radius	2.0×10^{-4} m
W (criterion exponent)	3.0
Max timestep	2.0×10^{-3} sec
Coupling interval	3.0 sec

Case	Production time	Critical hydraulic gradient	Bottomhole pressure
A1	3600 s	1.5E-5 m/s	10 MPa
A2	3600 s	1.5E-5 m/s	11 MPa

Reference Case A1: Animation



- Sand detachment
- Sand migration
- Clogging of pore throat



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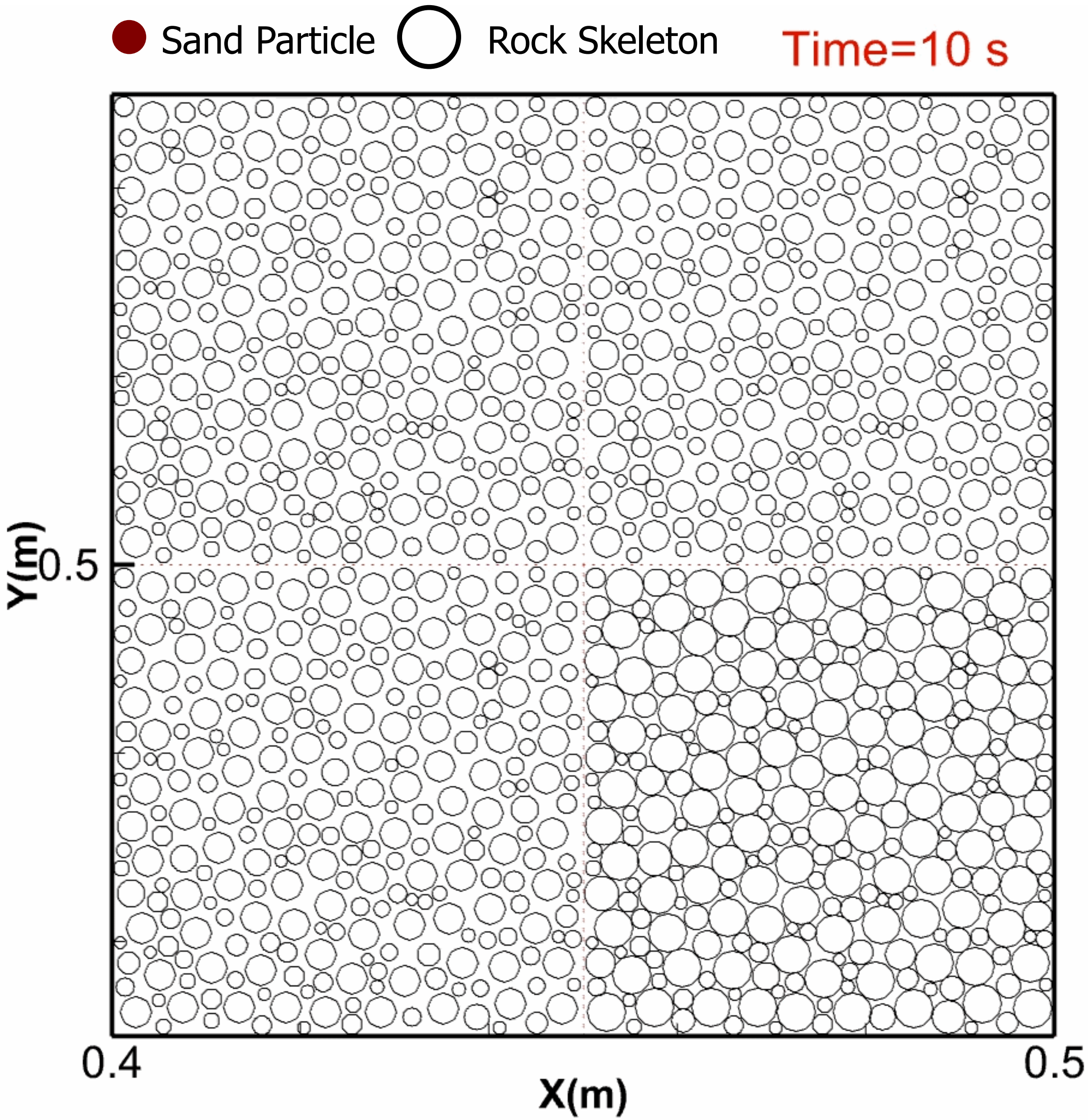

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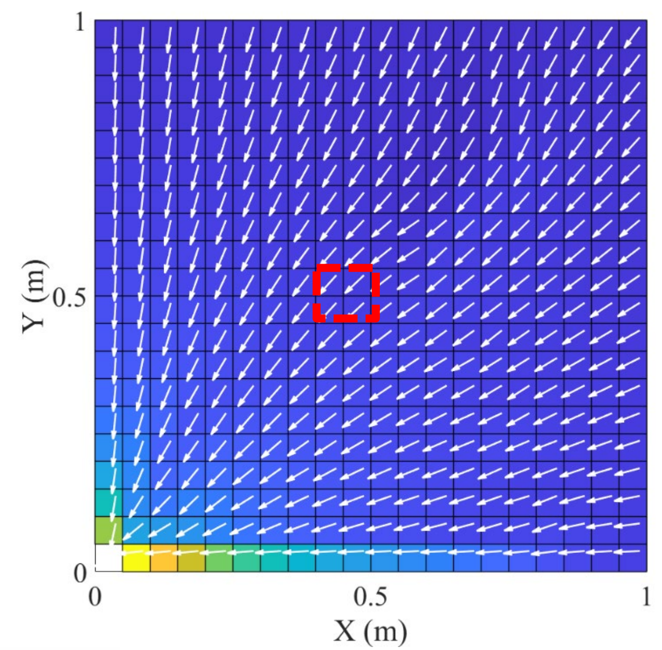

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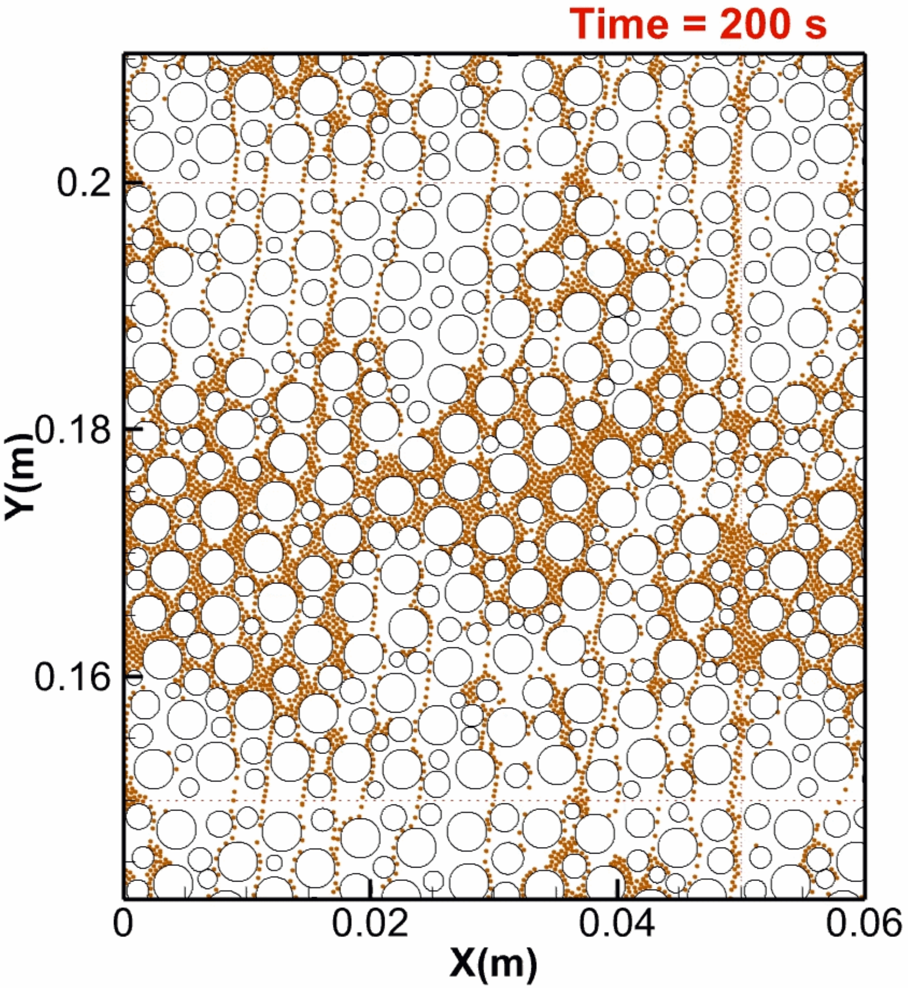
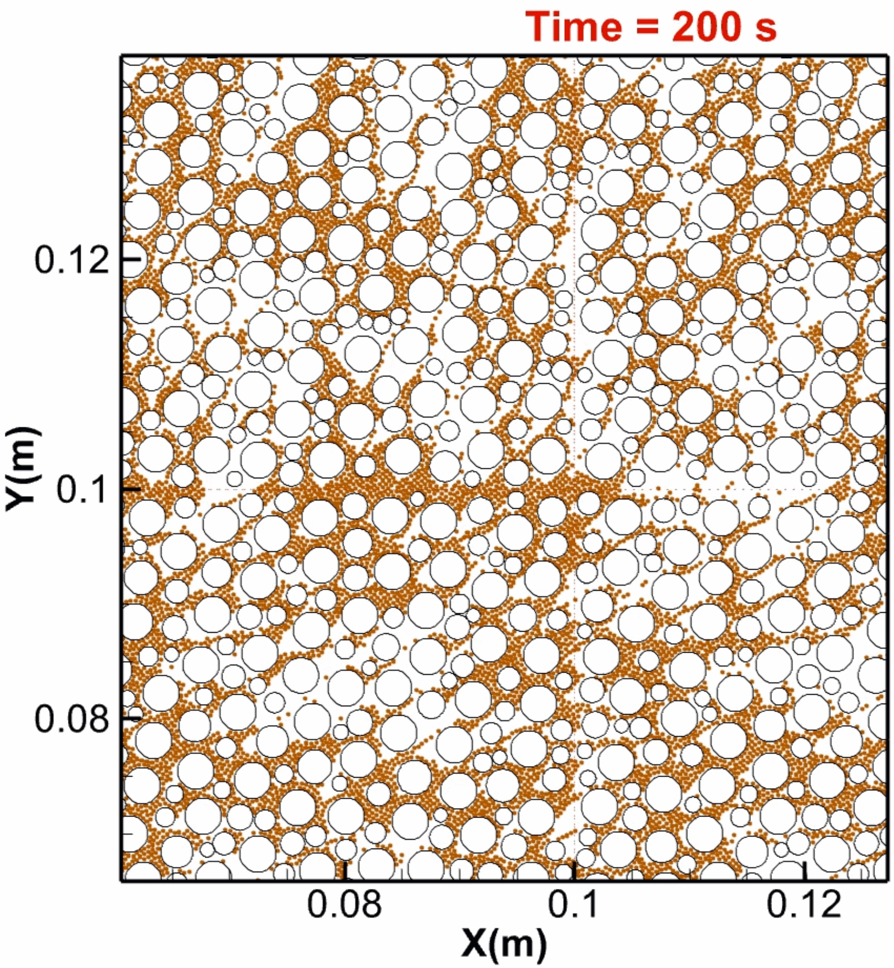
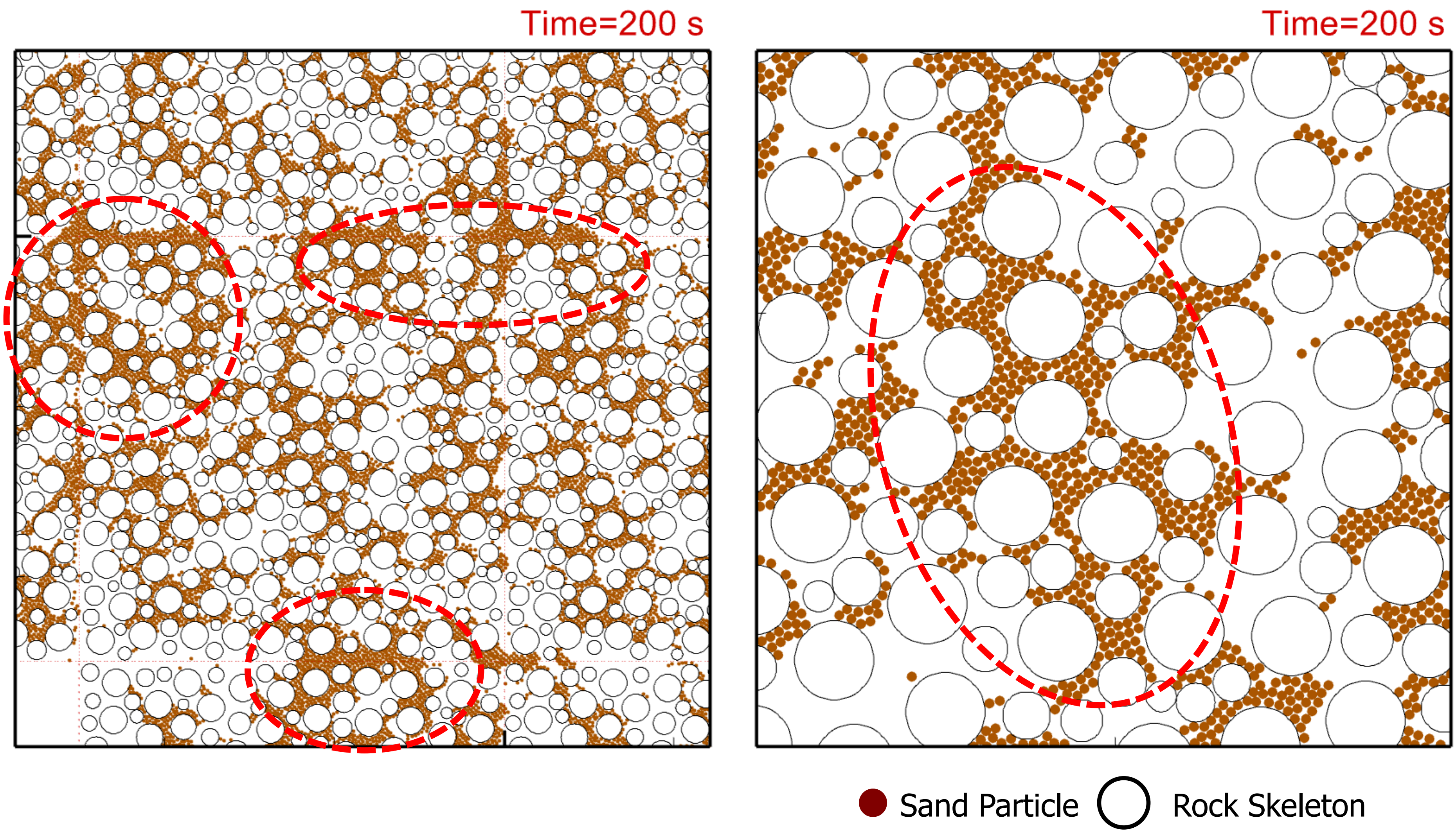


Unobstructed paths for particle transport

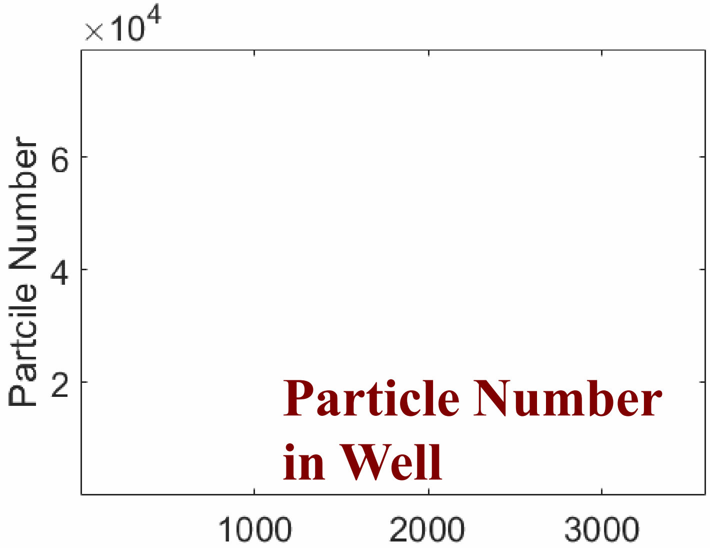


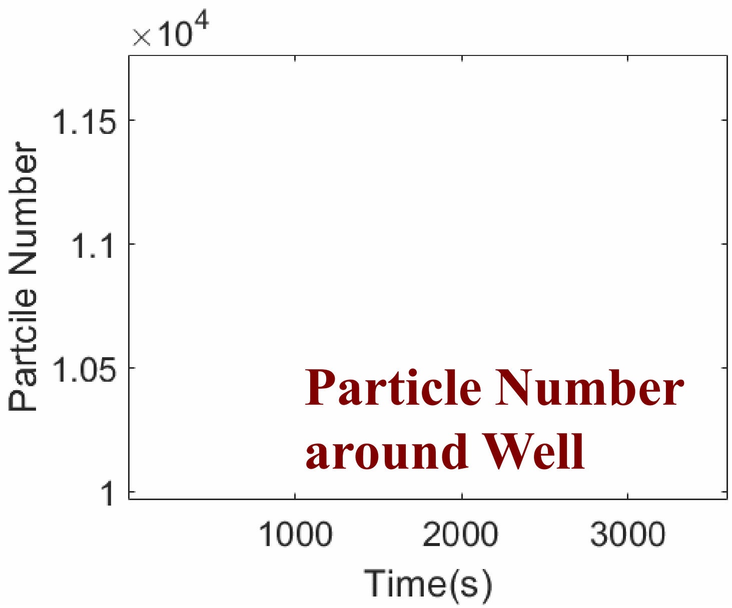
Particles clogging around the well

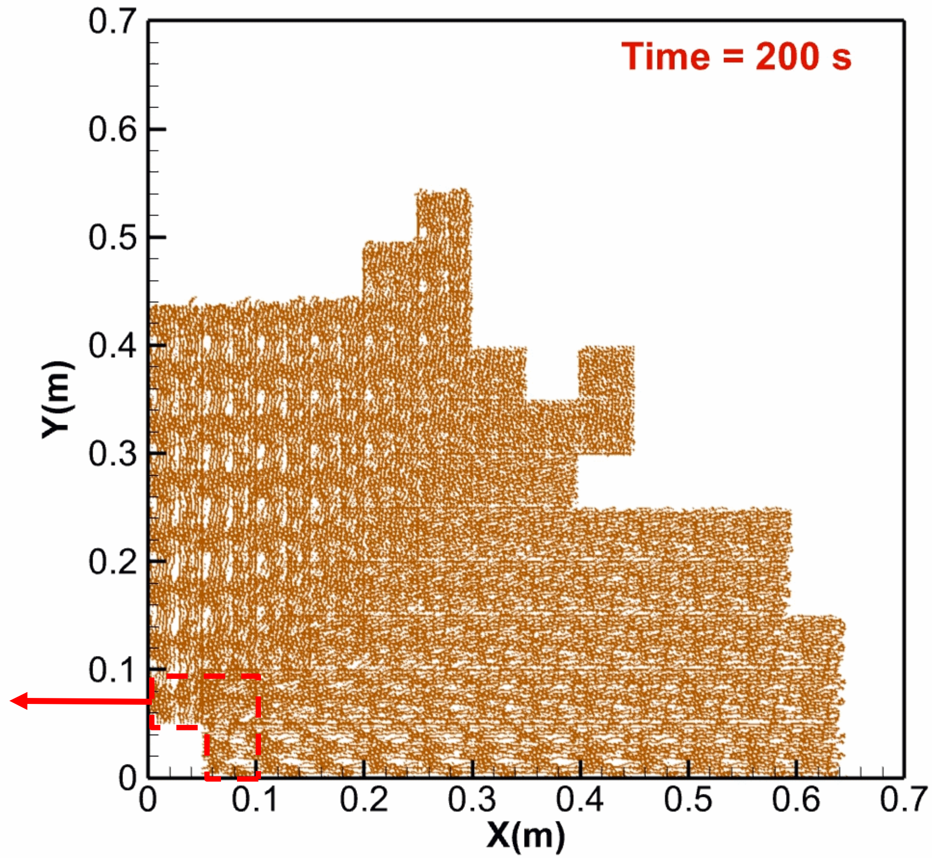
Reference Case A1: Detail View



Reference Case A1: Time Series Plots

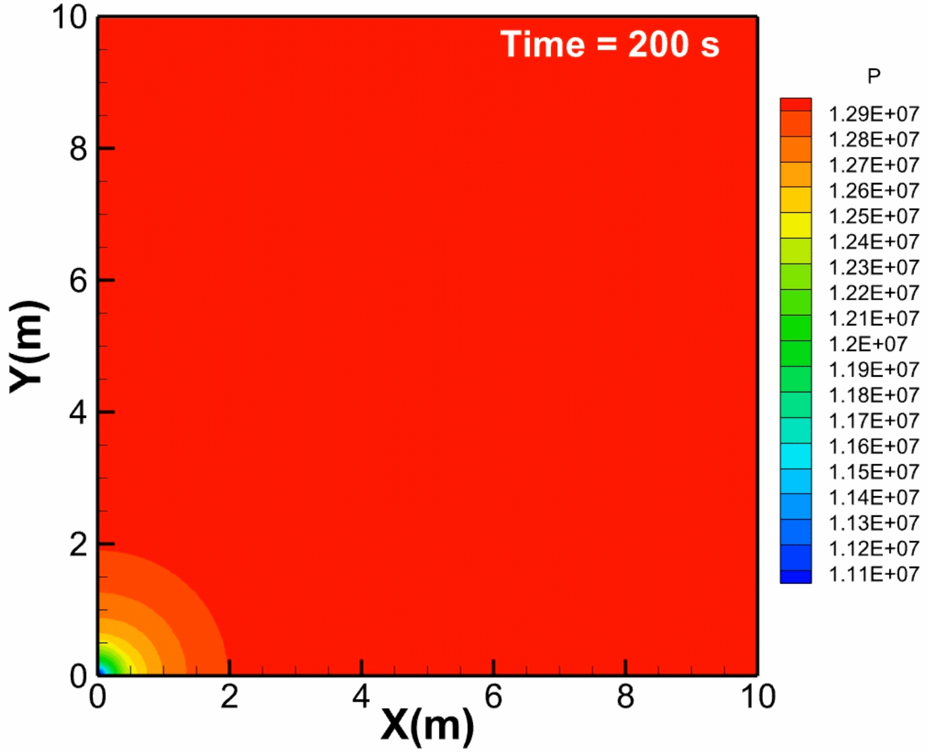


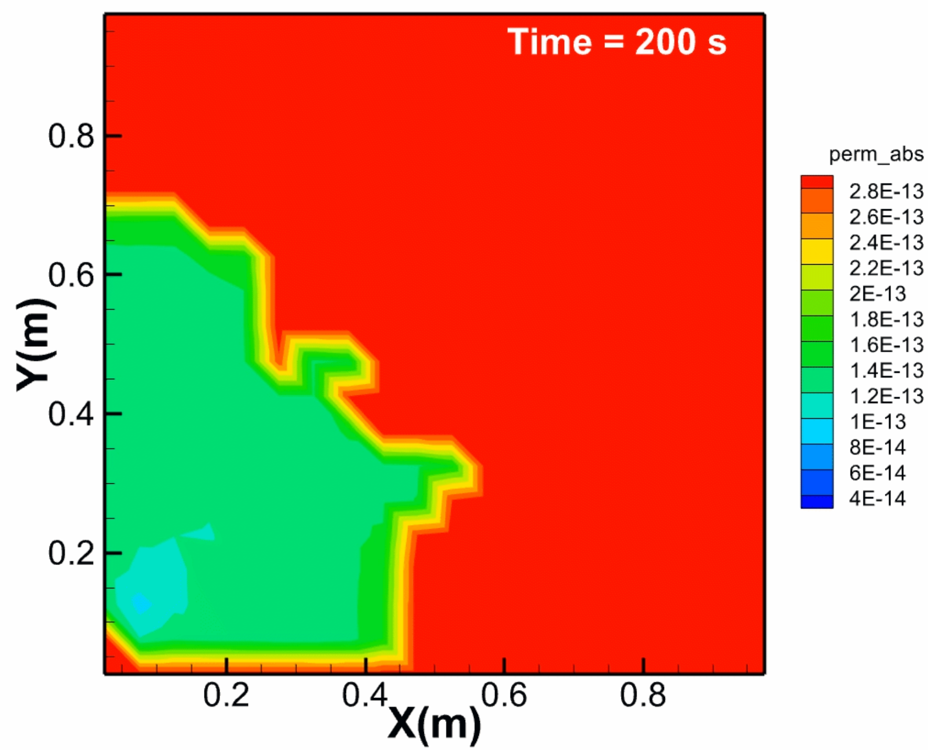




Sand migration in porous media

Reference Case A1: P&k Evolutions

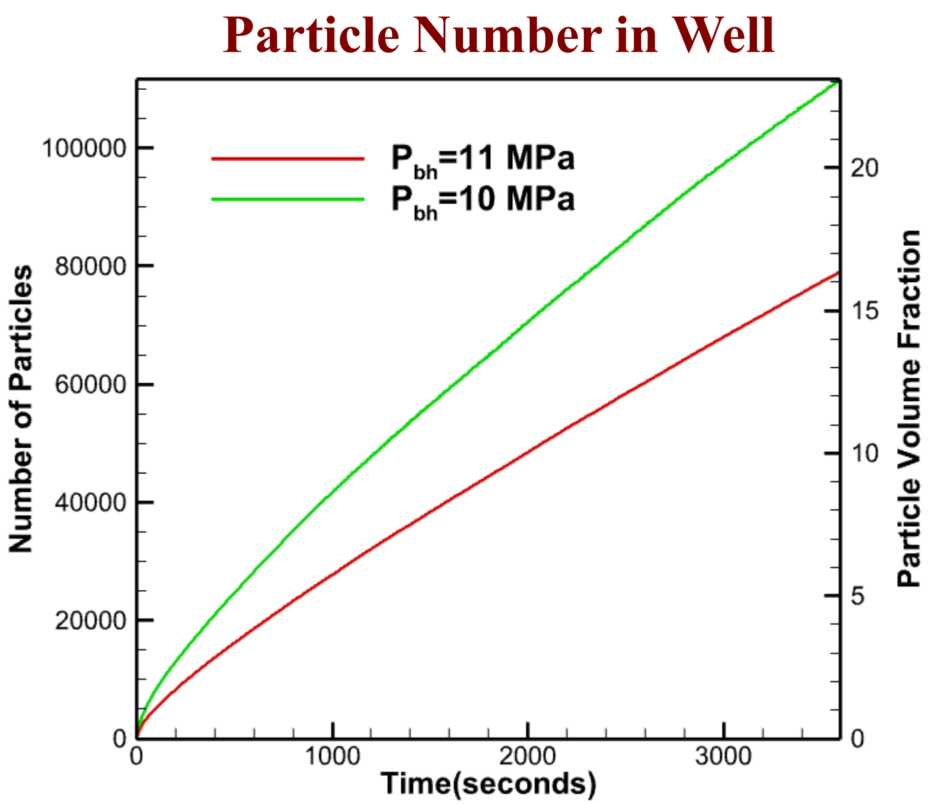


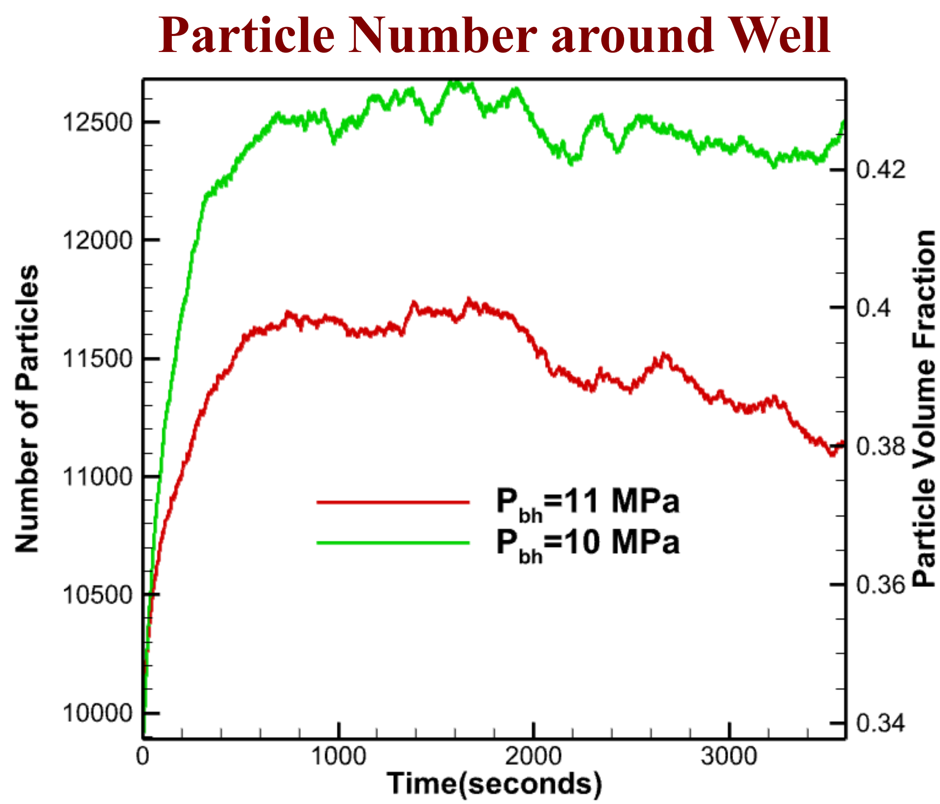


P-distribution: Production at a constant bottom-hole pressure

k-distribution: decreases due to particle clogging

Effect of Bottomhole Pressure on Sand Production

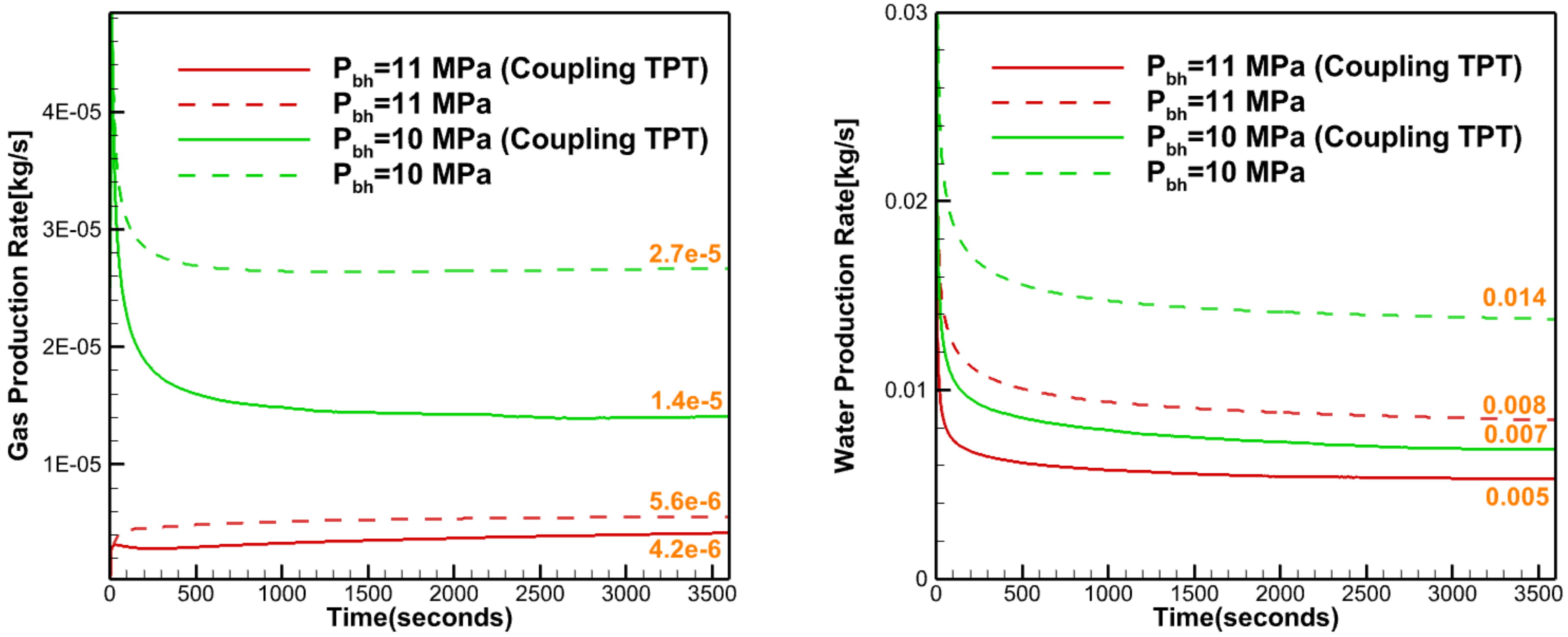




Decreasing bottom-hole pressure:

- corresponds to increasing sand production
- enhances particle clogging around the well

Effect of Bottomhole Pressure on Production Rates



- **Fluid production rates decrease with increasing sand accumulation in the well vicinity**
- **Variations in accumulated sand impact production rates**

Computational Cost

Factors affecting calculation cost

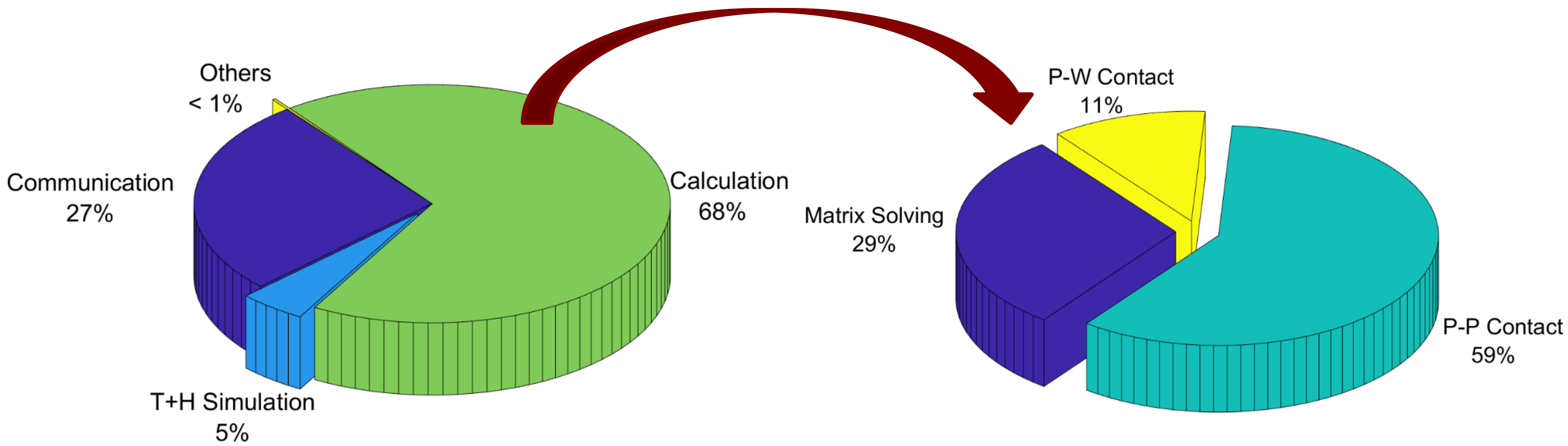
- **Timestep:** limited by the maximum fluid velocity
- **Number of particles:** limited by the average fluid velocity and particle detachment criterion
- **Elapsed time of each iteration:** limited by the number of particles
- **Number of processors**

Case	Num Proc	Time (s)	V_{cri} (m/s)	P_{bh} (Mpa)	Num Particles	Simulation Time (hour)
A1	96	3600	1.5×10^{-5}	11	**331,354**	**27.1**
A2	112	3600	1.5×10^{-5}	10	**552,256**	**54.2**

Computational Cost

Main subroutines

- **P-P contact**: Particle-Particle contact searches
- **P-W contact**: Particle-Porous media wall contact searches
- **Matrix Solving**: Calculations of forces; integration of Euler’s equation
- **Communication**: Sharing information across processors



A2: Overall Time Statistics **Time Statistics of PT Calculations**

Challenges

- Need for better mathematical expressions describing the particle detachment criterion (hydraulic gradient, strain, hydrate saturation, etc.)
- Wide variability of timestep adjustments (several affecting factors)
- Realistic grain structure of porous media
- Need for code validation against experimental results (?)
- Code enhancement to optimize computational efficiency
- Extension to 3D