Improved Partial Coupling for Multi-Phase Flow Solvers

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Outline

- Numerical approach/coupling methods
- The need for revised partial coupling?
- Study cases
  - Fluidized bed
  - Turbulent open channel
- Conclusions

Numerical approach (CFD-DEM)

- Volume averaged NS eqs.
  - Coupling through drag & void fractions
- Equation of motion
  - Point force models are used
  - Collision model to resolve pp & pw interactions
- Coupling techniques
  - Full coupling (ε + forces in fluid Eqs.)
  - Partial coupling (only forces in fluid Eqs., ε =1)
    - More stable
    - Faster convergence

Fluid

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \vec{\nabla}.(\varepsilon\rho\vec{u}) = 0$$

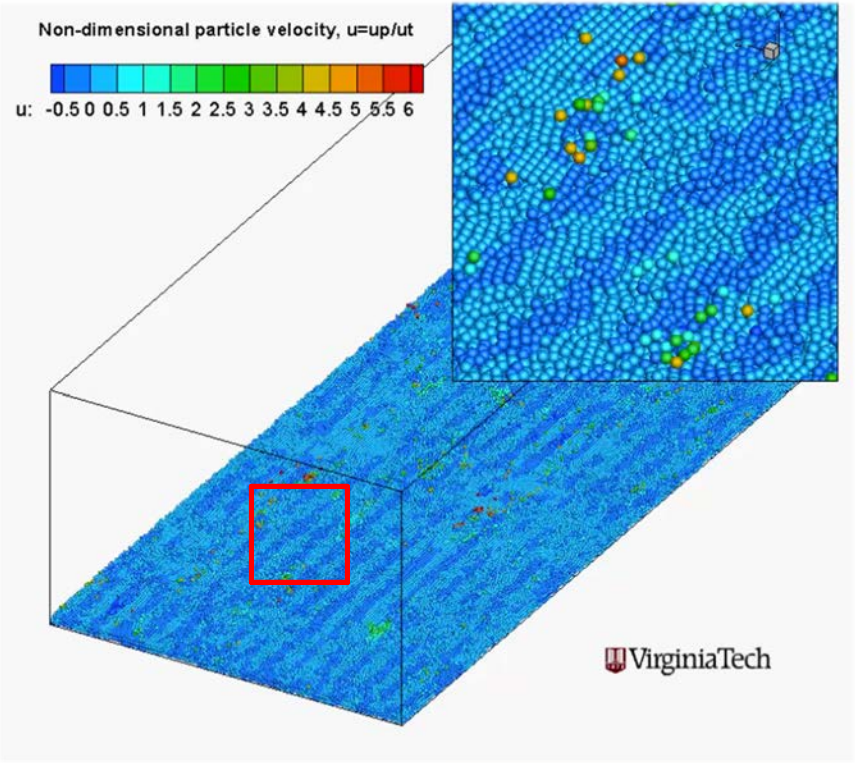
$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \vec{\nabla}.(\varepsilon\rho\vec{u}\vec{u}) = -\vec{\nabla}p + \vec{\nabla}.(\varepsilon\bar{\bar{\tau}}) + \rho\vec{g} - \frac{\sum_{N_p}\vec{F}_{drag}}{\forall_c}$$

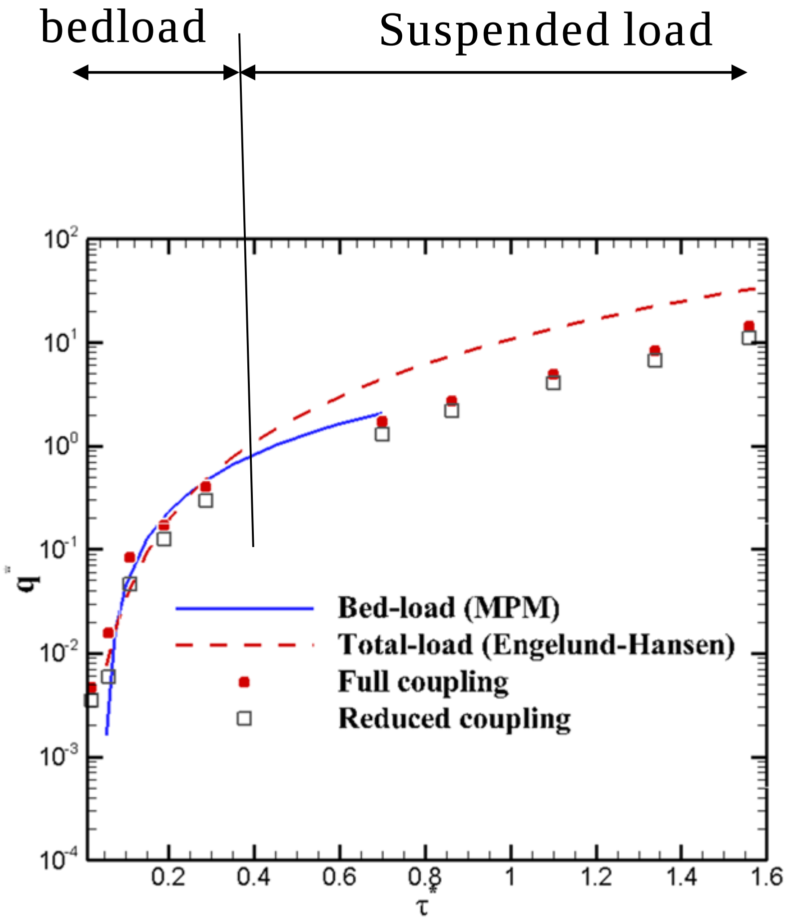
Dispersed phase

$$m_p\frac{d\vec{u}_{p,i}}{dt} = \vec{F}_{grav,i} + \vec{F}_{drag,i} + \sum\vec{F}_{contact}$$

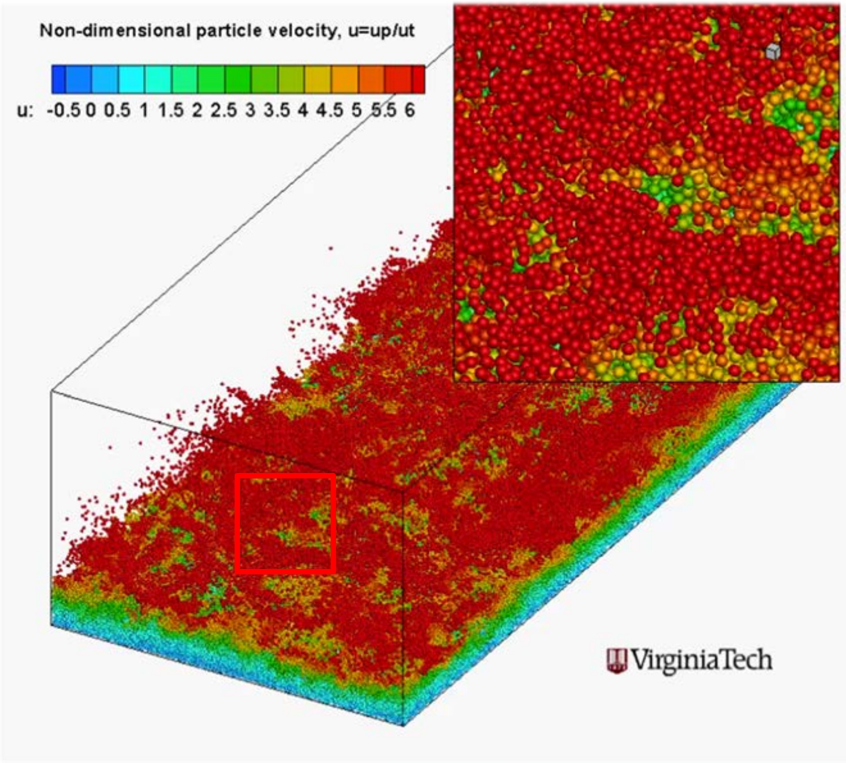
Coupling effect in turbulent open channel flow

Bedload





Suspended load



Einstein number; $q^* \equiv \frac{q_{sx}}{\left(\left(\frac{\rho_s}{\rho}-1\right)gd^3\right)^{1/2}}$

Shields parameter; $\tau^* \equiv \frac{\rho u_\tau^2}{(\rho_s-\rho)gd}$

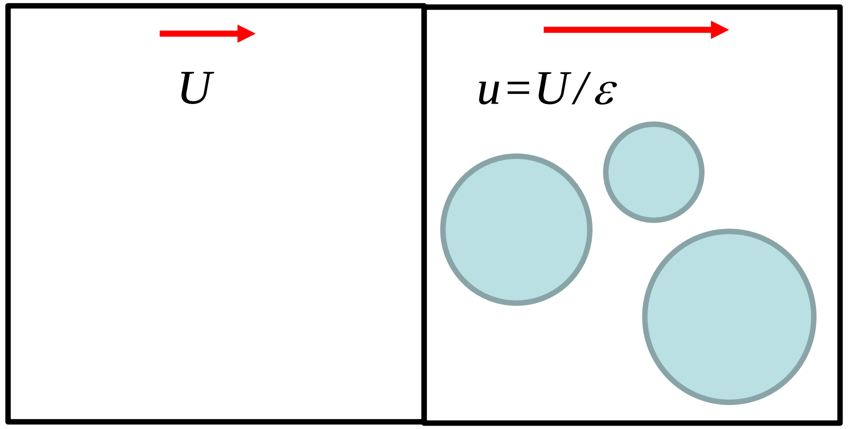
Revised partial coupling

- Possible cause of the under-prediction of results is that the interstitial velocity used to calculate the drag becomes smaller than what it should be
- $\vec{f}_{Drag} = \frac{\beta}{(1-\varepsilon)\rho_p}(\vec{u} - \vec{u}_p)$
- A possible remedy is by introducing the effect of void fraction on the interstitial velocity in the drag formulation

u : interstitial fluid velocity

U : Undisturbed/superficial velocity

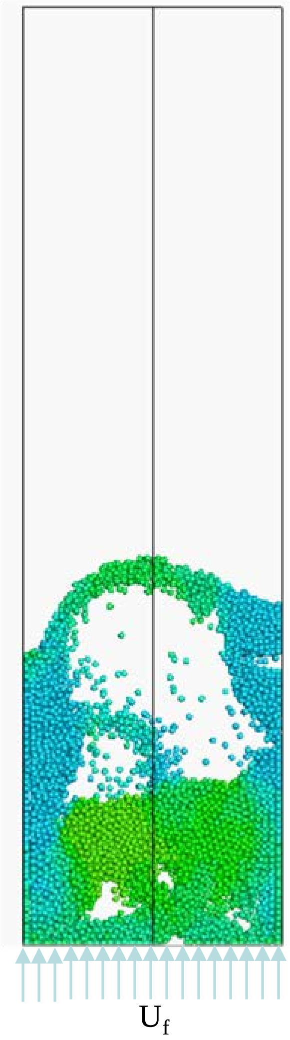
Interstitial velocity $u = U/\varepsilon$



Case-1: Fluidized bed

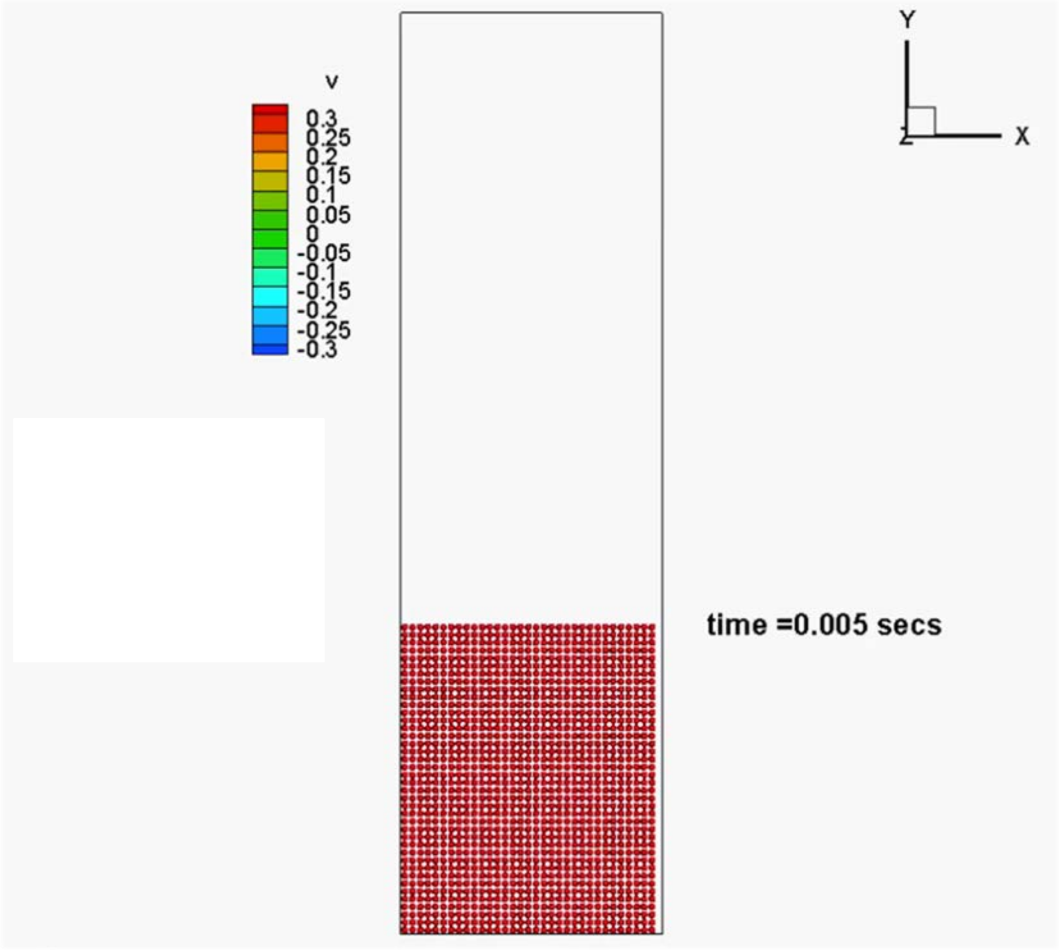
- Muller et al. (2009) Experiment
  - 44 mm × 160 mm × 10 mm
  - U_f=0.9m/s (~$3U_{mf}$)
  - 9342 particles

Particles properties (Poppy seeds)	
Diameter	1.2 mm
Density	1000 kg/m^3
Friction coeff.	0.1
Restitution coeff.	0.98 m/s
Stiffness coeff.	100 N/m
Fluid properties (Air)	
Density	1.205 kg/m^3
viscosity	1.8×10^{-5} kg.$m^{-1}s^{-1}$

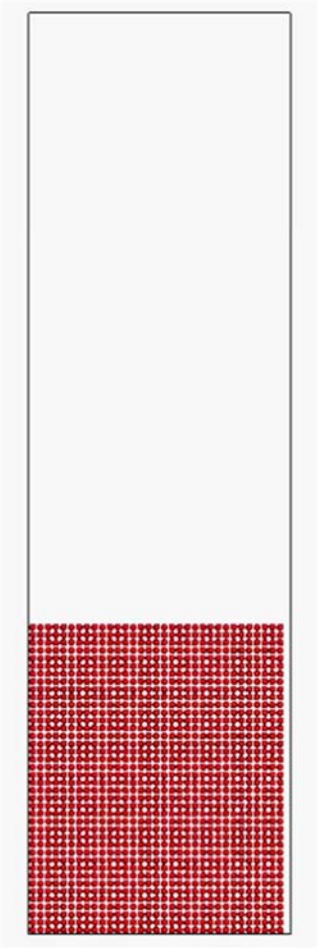


Fluidized bed: Animation

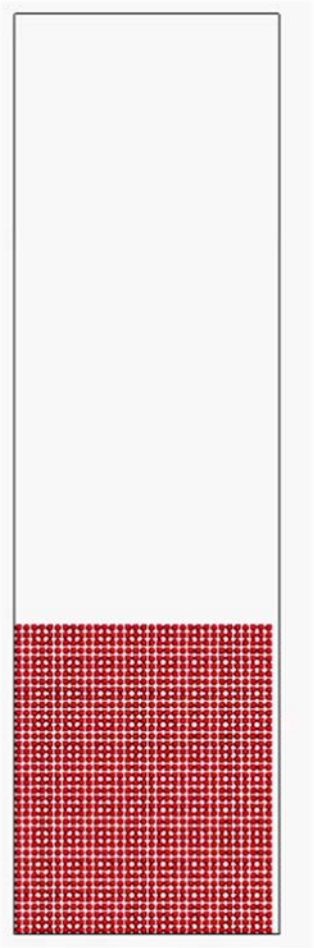
Full coupling



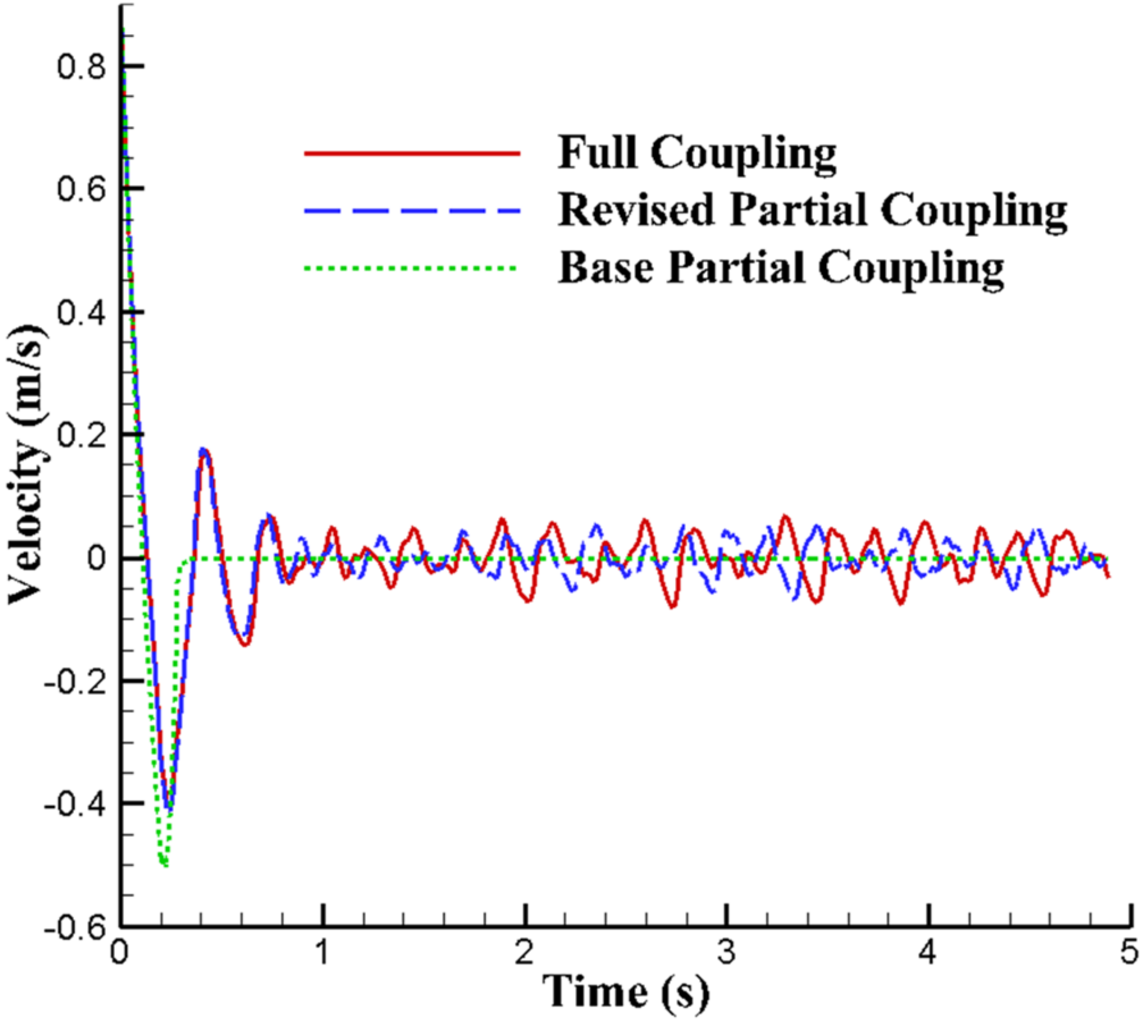
Revised PC



Base PC

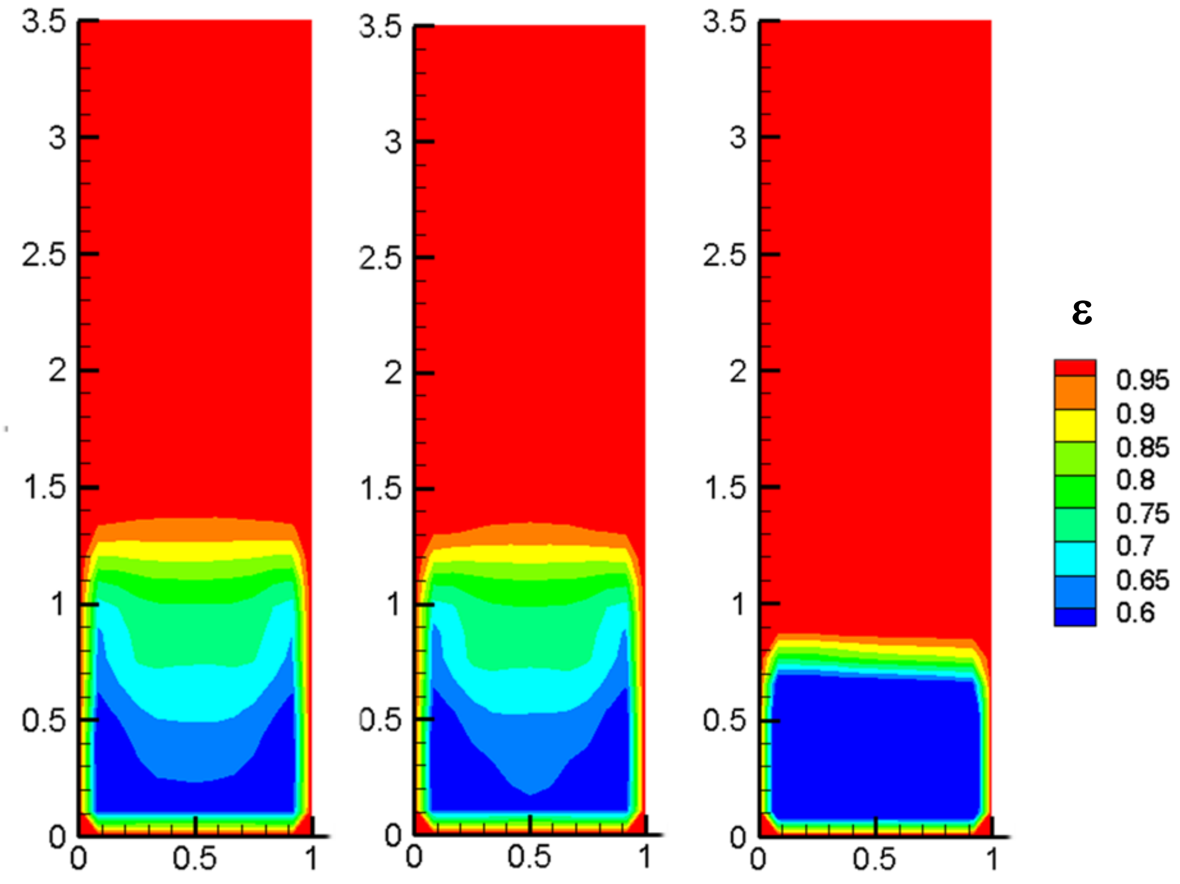


Fluidized bed: Time series

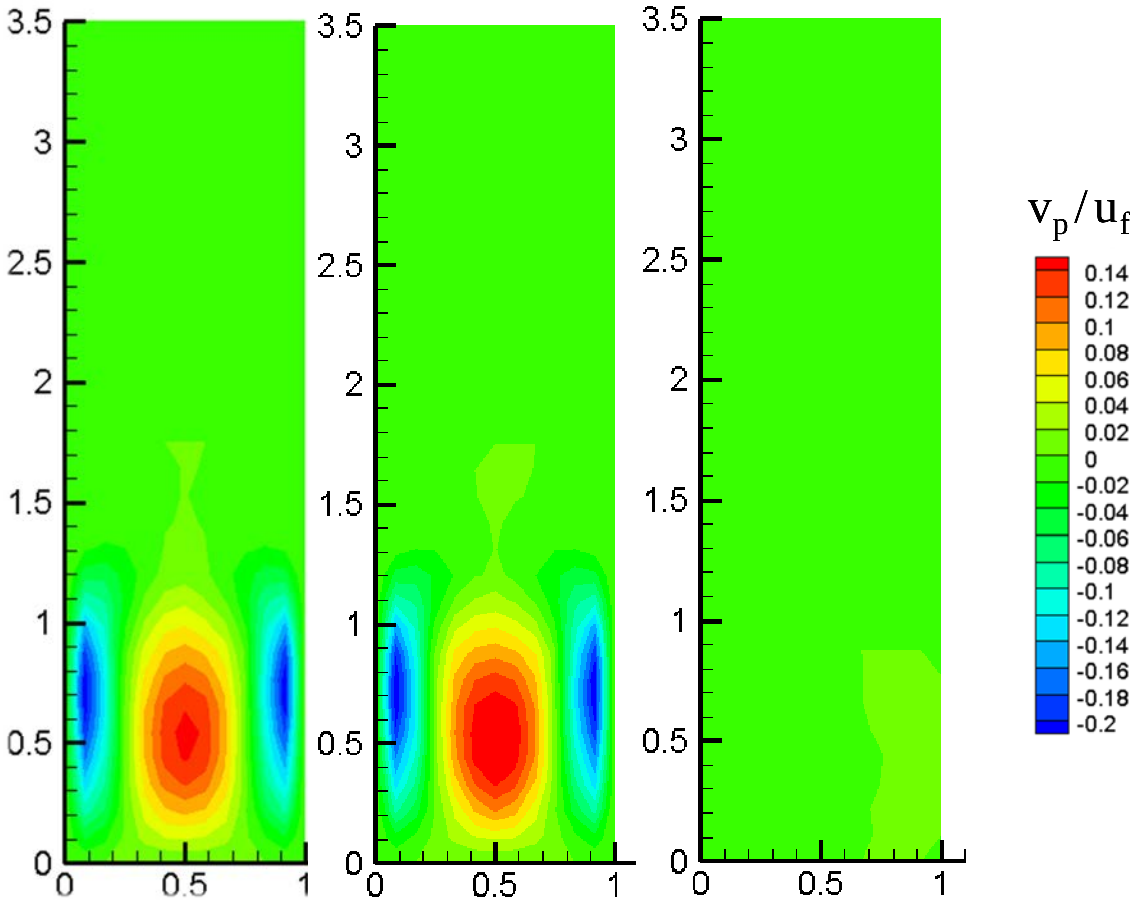


Fluidized bed: Averaged results

Void fraction



Solids velocity

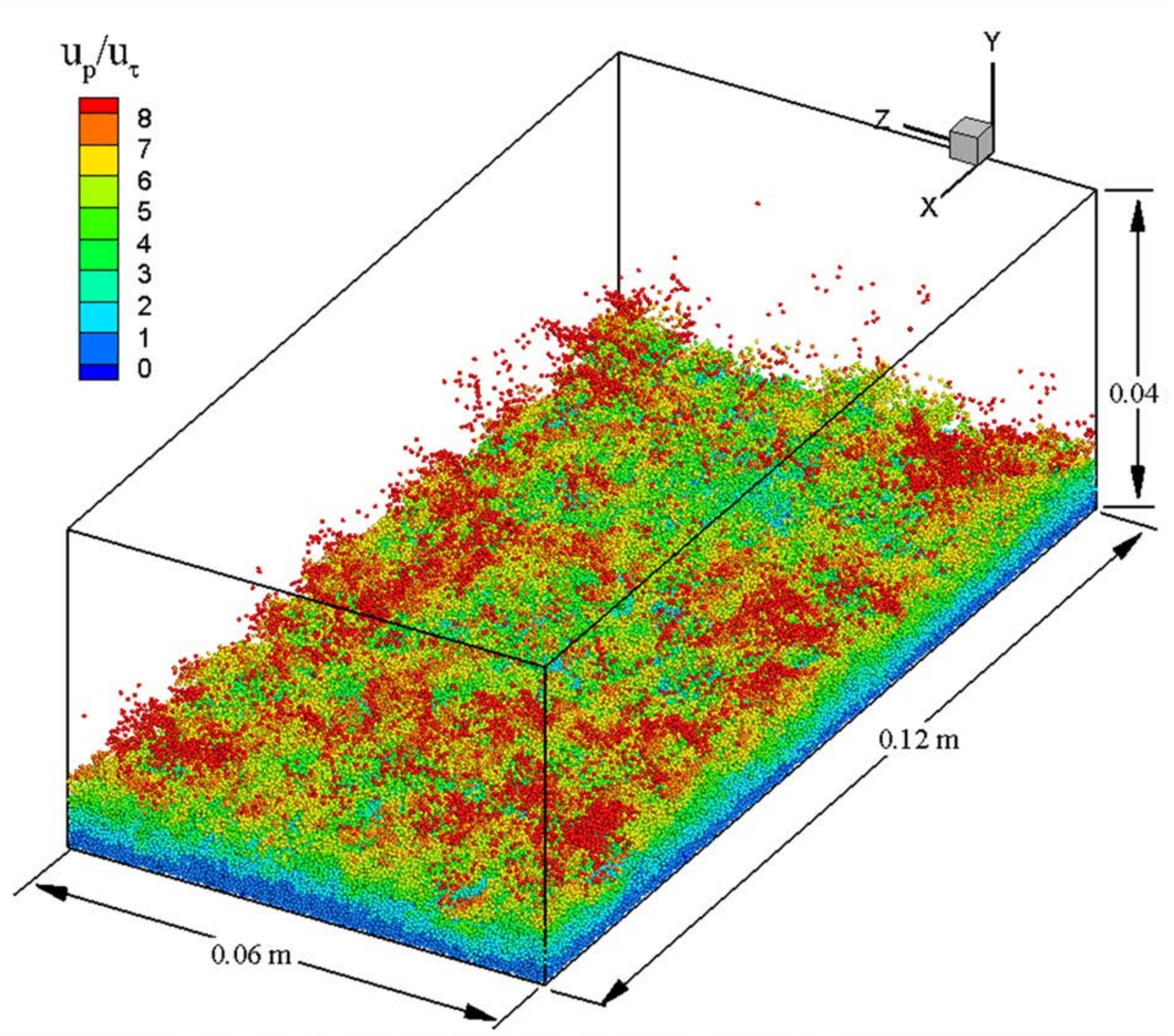


Case-2: Turbulent open channel flow

- Schmeeckle 2014
  - Medium sand in water

	u_τ	Re_τ	Re_b	τ^*	u_τ/ω
Run-1	0.013	584	7,820	0.0209	0.239
Run-2	0.0486	2170	22,286	0.288	0.848
Run-3	0.113	5080	53,116	1.558	1.558

Parameter	value
Particle diameter	0.5 mm
Coefficient of restitution	0.01
Particle density	2650 kg/m^3
Friction Coefficient	0.6
Stiffness coefficient	100 (N/m)
Particle time step (10 sub steps)	5.3×10^{-5} s

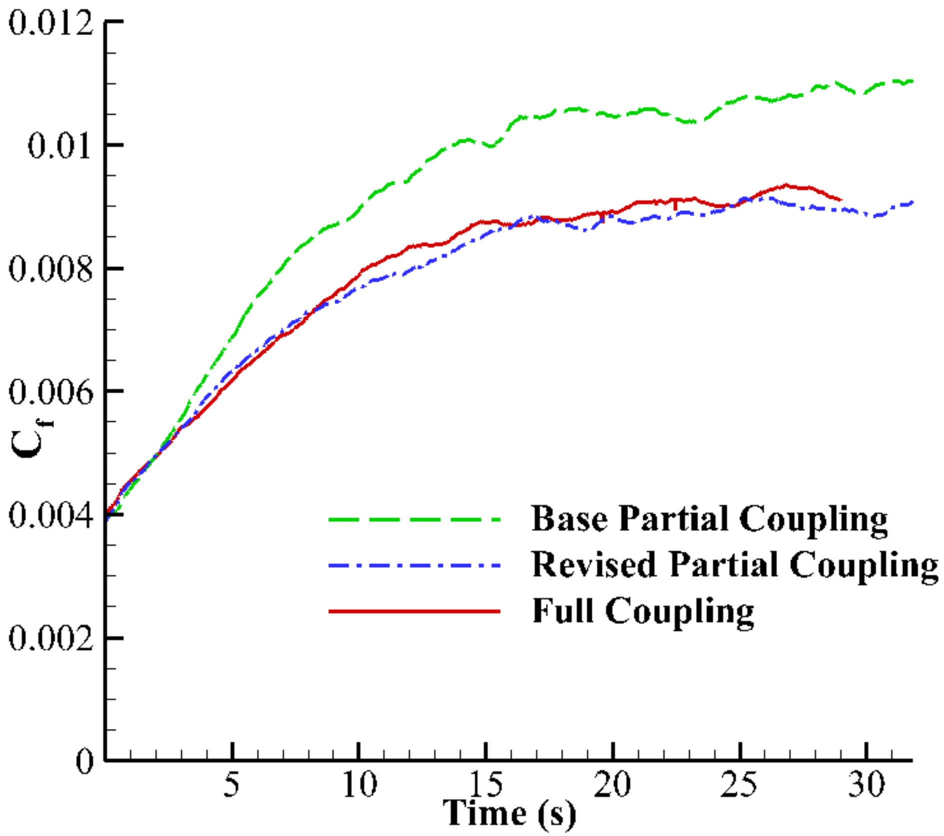


Open channel: Averaged results

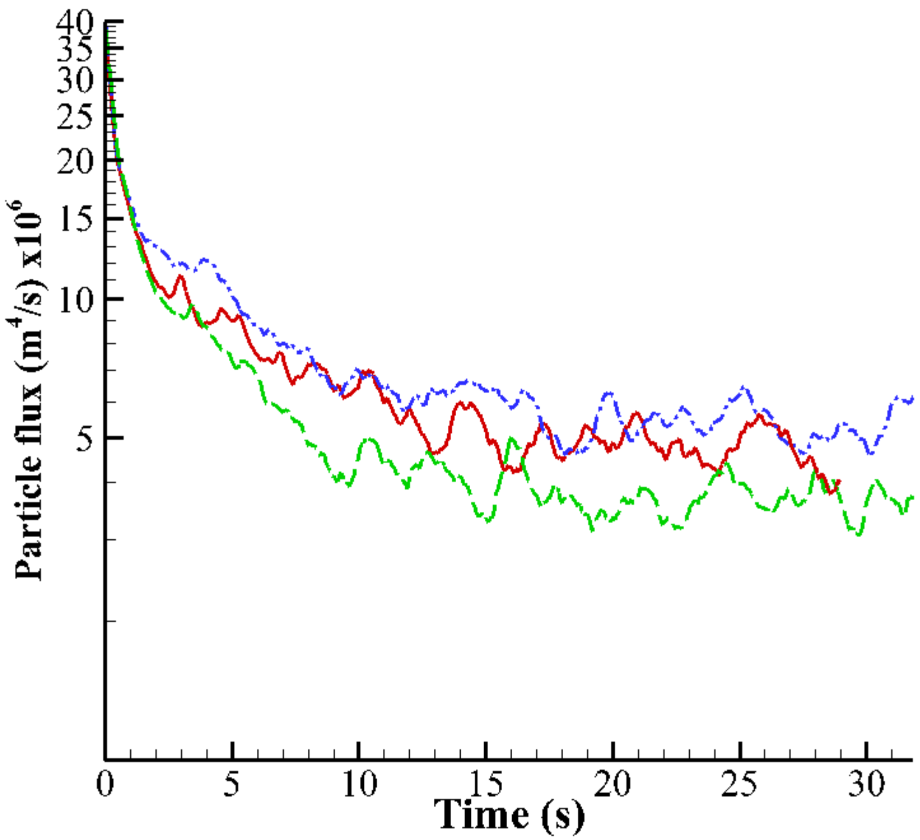
			Full coupling	Base particle coupling	Revised partial coupling
Run-1 (τ^*= 0.209)	C_f	Mean	0.005582	0.006176	0.006096
		Diff. %	--	10.6%	9.2%
	Particle flux (m^4/s)	Mean	1.5×10^{-9}	1.14×10^{-9}	1.26×10^{-9}
		Diff. %	--	-24.4%	-16.2%
Run-2 (τ^*= 0.288)	C_f	Mean	0.009488	0.0096	0.009862
		Diff. %	--	1.2%	3.9%
	Particle flux (m^4/s)	Mean	1.31×10^{-7}	9.47×10^{-8}	1.28×10^{-7}
		Diff. %	--	-27.8%	-2.2%
Run-3 (τ^*= 1.558)	C_f	Mean	0.009151	0.010747	0.008956
		Diff. %	--	17.4%	-5.6%
	Particle flux (m^4/s)	Mean	4.75×10^{-6}	3.7×10^{-6}	5.4×10^{-6}
		Diff. %	--	-21.5%	14.7%

Open channel: Time series

Channel friction ($C_f = (u_\tau/u_b)^2$)



Sediment flux (m^4/s)



Simulation speed-up

- Fluidized bed
  - overall speed-up ~27% (20% at stationary conditions)
  - time to fluid solution ~ 44% (41% at stationary conditions)

- Chanel flow calculation (suspended load case)
  - overall speed-up~23%
  - time to fluid solution ~ 54%

Conclusions

- Revised/improved partial coupling shows an improvement of the results of bubbling fluidized bed simulation and channel flow compared to base partial coupling

- >40% saving in solution time is achieved when using revised partial coupling as a result of better convergence behavior

- Other point force models can be treated similarly

Acknowledgement

- Libyan Ministry of Higher Education and Scientific Research
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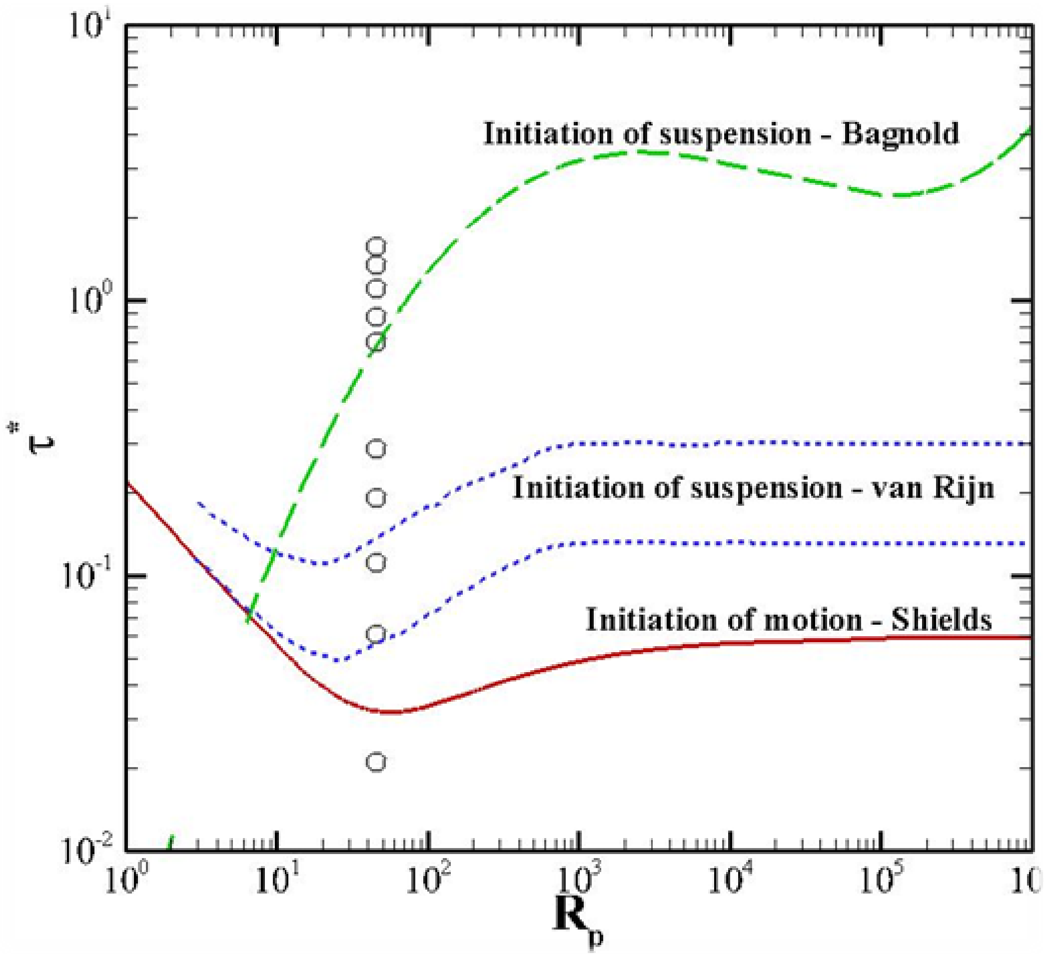
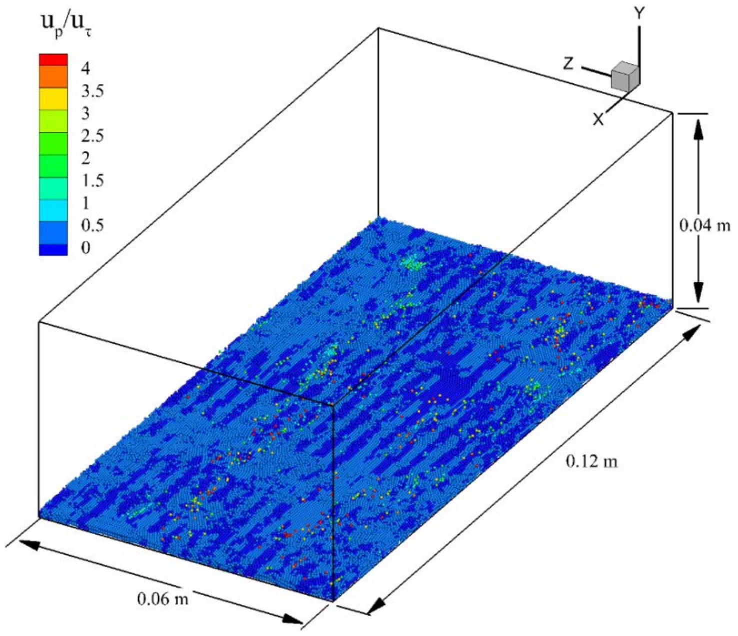
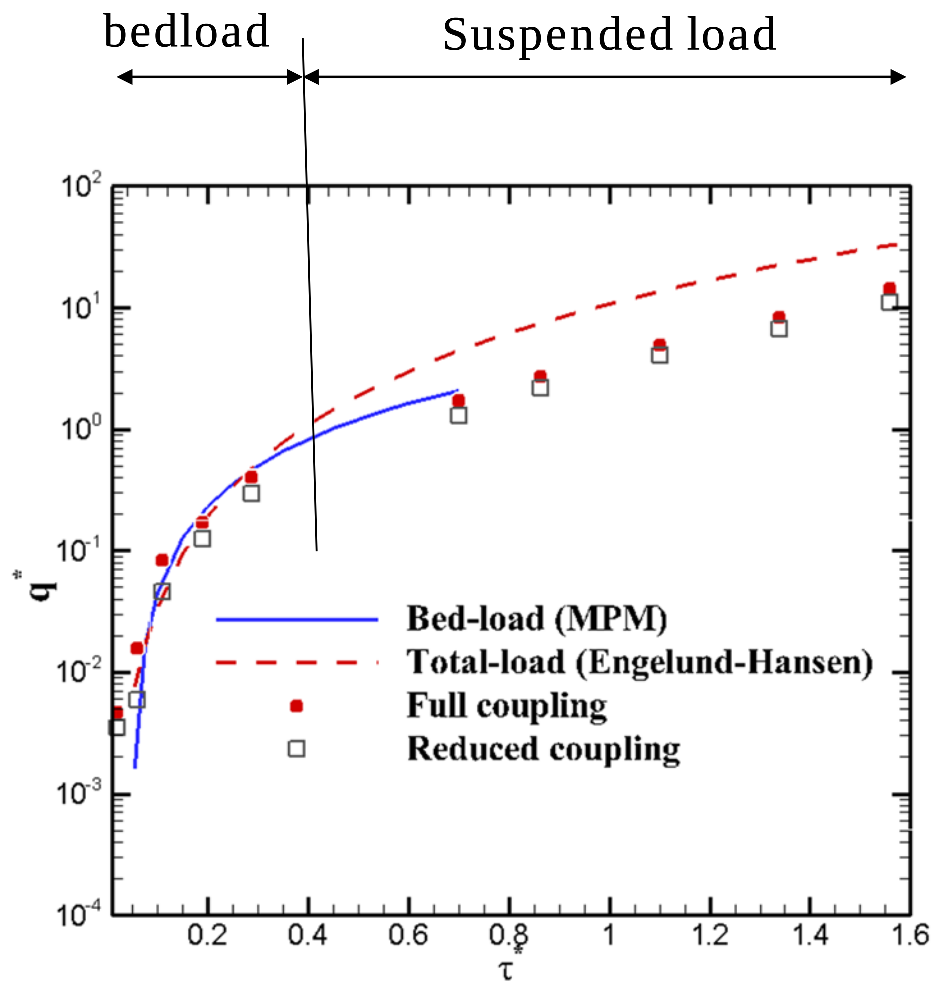
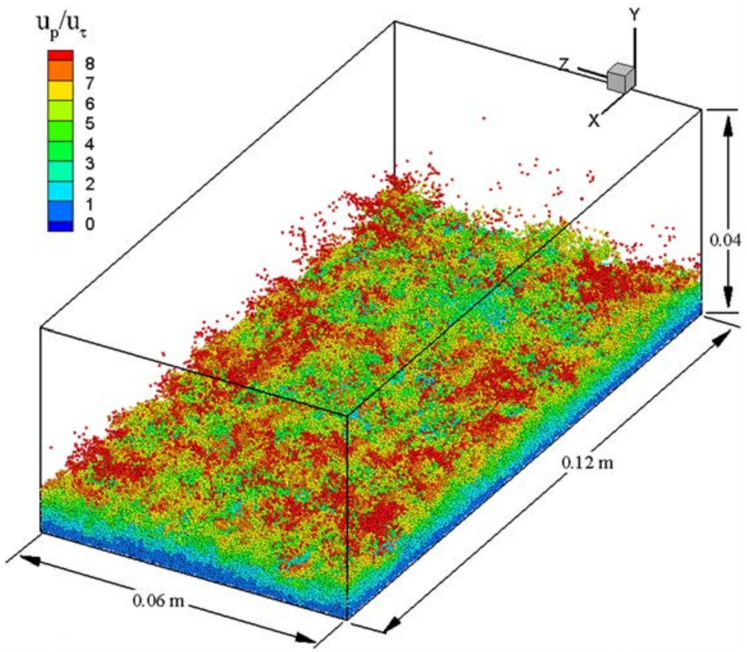
Thank You


Initiation of suspension - Bagnold
Initiation of suspension - van Rijn
Initiation of motion - Shields
τ*
R_p
10^1
10^0
10^-1
10^-2
10^0
10^1
10^2
10^3
10^4
10^5

Coupling effect in turbulent open channel flow







Einstein number; $q^* \equiv \frac{q_{sx}}{\left(\left(\frac{\rho_s}{\rho}-1\right) g d^3\right)^{1/2}}$

Shields parameter; $\tau^* \equiv \frac{\rho u_\tau^2}{(\rho_s-\rho) g d}$

Simulation speed-up: Fluidized bed

coupling	Time steps	Total time (hours)	Speed-up in total time	Press. Sol. Time (s)	Speed-up in Press. Sol. time
Full coupling	500k-init	59	NA	0.4863×10^4	NA
Full coupling	500k-avg	64	NA	0.5793×10^4	NA
Revised-PC	500k-init	39	-34%	0.2541×10^4	-48%
Revised-PC	500k-avg	51:18	-20%	0.3446×10^4	-41%
Base-PC	500k-init	51:30	-13%	0.2170×10^4	-55.4%
Base-PC	500k-avg	94	47%	0.4051×10^4	-30%

Simulation speed-up: Open channel

Simulation times for 50k time steps (time 20-25s)

		Pressure conv. time (s)	Total time (s)	% DEM	Simulation speed-up	Pressure convergence speed-up
Run-1*	Full	1115.82	372500	65.7	NA	0.0
	PC-revised	132.734	275700	88.1	-26.0	-88.1
	PC-base	111.308	353000	88.3	-5.2	-90.0
Run-2*	Full	617.115	230900	67.2	NA	0.0
	PC-revised	106.584	131650	78.2	-43.0	-82.7
	PC-base	118.14425	245825	85.8	6.5	-80.9
Run-3	Full	215.731	187500	81.0	NA	0.0
	PC-revised	98.524	144800	78.0	-22.8	-54.3
	PC-base	100.729	254900	87.1	35.9	-53.3

** Runs on different clusters*