A Particle-based Model of Flow-Induced Scour

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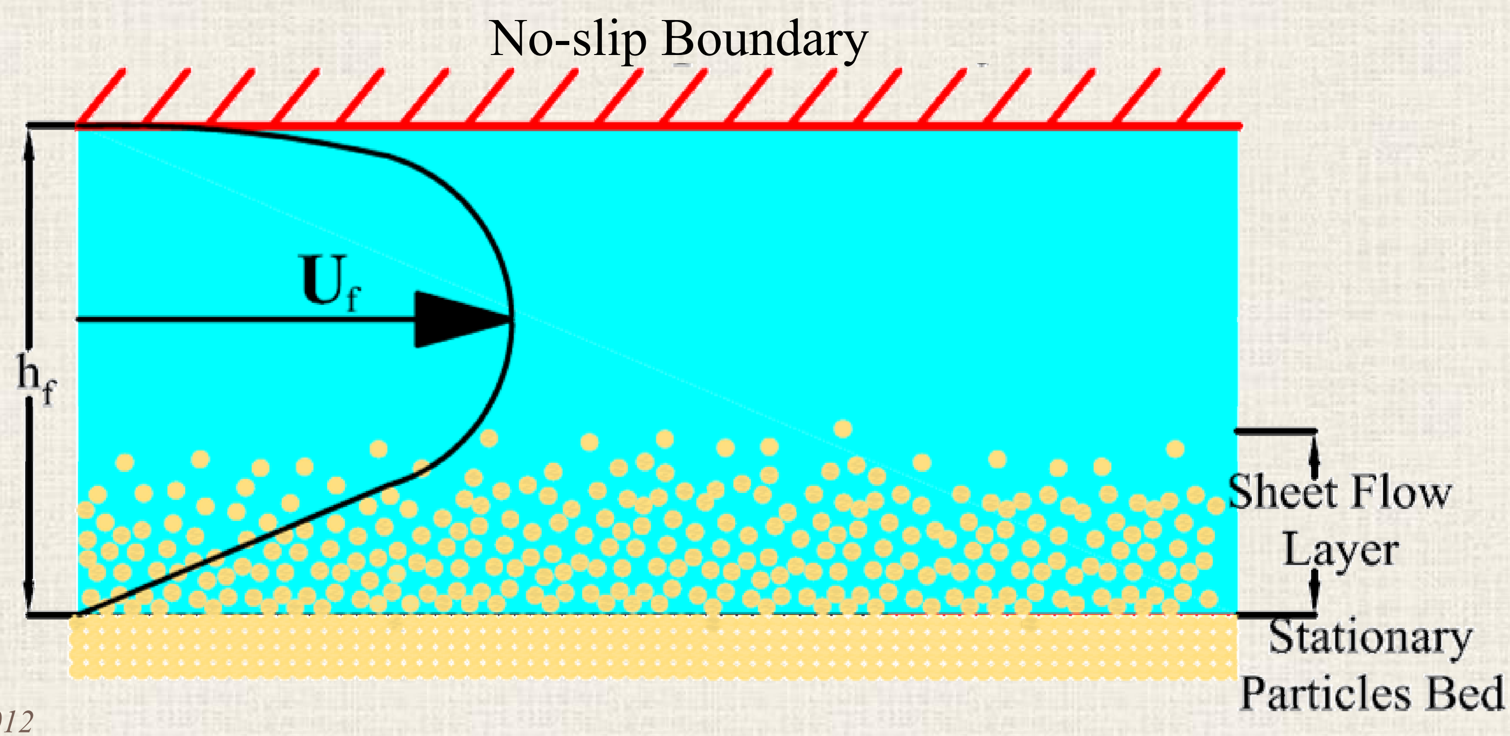
Introduction

- Experimental observations show that if the fluid flow velocity exceeds a certain value, the particles in the upper layers of the bed would start moving (sheet flow).
- There is a lack of understanding of many characteristics of the particles and fluid interaction especially the top layers of particles (sheet flow layer).



Introduction

- The interaction between the fluid and solid phases involves high fluid velocities and transient variations in the properties of the fluid and solid phases as the erosion occurs.

- We present a three-dimensional fully coupled transient fluid-particle model to simulate flood-induced erosion of a particle bed.

- A parallel experimental program provides pore-scale fluid velocity using digital particle image velocimetry (DPIV) for comparison with the numerical results.

- We present the response of a particle bed to Poiseuille flow conditions to get a better understanding of the dynamics of the sheet flow layer by tracking particle and fluid velocities.

Coupled Fluid Particle Model

Continuum fluid phase:

- Solved using FEM code
- Averaged Navier-Stokes equations (Jackson, 2000; El Shamy 2004):

Continuity

$$\frac{\partial n}{\partial t} + \nabla.\left(n\bar{\mathbf{v}}_f\right) = 0$$

Momentum

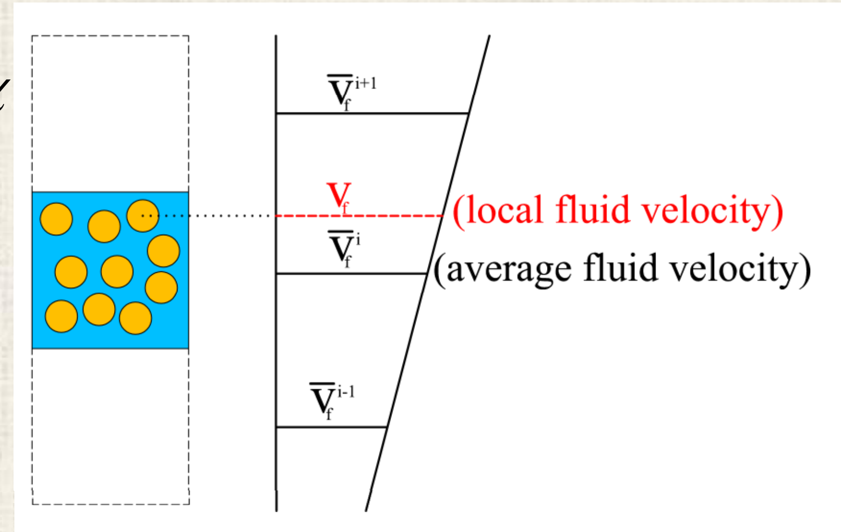
$$\rho_f\left(\frac{\partial(n\bar{\mathbf{v}}_f)}{\partial t} + \nabla.\left(n\bar{\mathbf{v}}_f\bar{\mathbf{v}}_f\right)\right) = -n\nabla\bar{p}_f\boldsymbol{\delta} + \mu_f\nabla^2(n\bar{\mathbf{v}}_f) - \bar{\mathbf{f}}_{f-p} + n\rho_f\mathbf{f}_g$$

$\bar{\mathbf{f}}_{f-p}$: Fluid-particle interactions

Fluid Phase

- Forces applied by the fluid on the particles:
  - Drag force f_{drag} (*Di Felice, 1994; Xu, 1997*):

$$\mathbf{f}_{drag} = \left(\frac{1}{8} C_d \rho_f \pi d_p^2 \left|\mathbf{v}_f - \mathbf{v}_p\right|(\mathbf{v}_f - \mathbf{v}_p)\right) n^{-\chi}$$

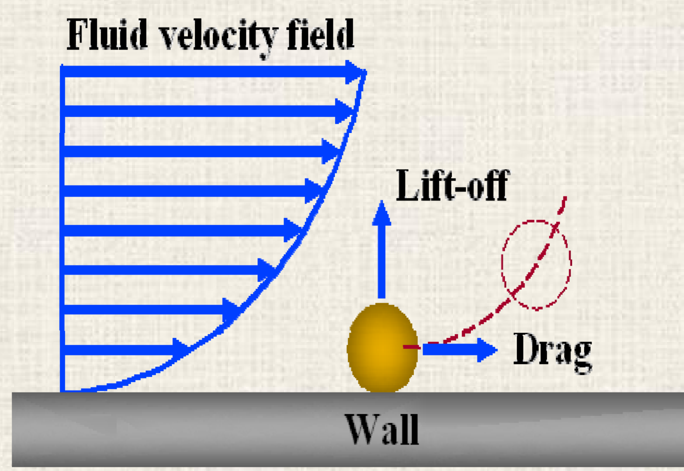


  - Lift force f_l (*Saffman, 1965 & 1968*):

$$\mathbf{f}_l = 1.62(\mathbf{v}_f - \mathbf{v}_p) d_p^2 \sqrt{\rho_f \mu_f u^*}\,\mathrm{sgn}(u^*)$$

$$\bar{\mathbf{f}}^i_{f-p} = \frac{\sum_j (\mathbf{f}^j_{drag} + \mathbf{f}^j_l)}{V_i}$$

$$\mathbf{f}_{fluid} = (\mathbf{f}_{drag} + \frac{1}{6}\pi d^3 \nabla \bar{\mathbf{p}}_f) + \mathbf{f}_l$$



Coupled Fluid Particle Model

Discrete solid phase:

- Solved using DEM code
- Newton's second law of motion :

Linear momentum

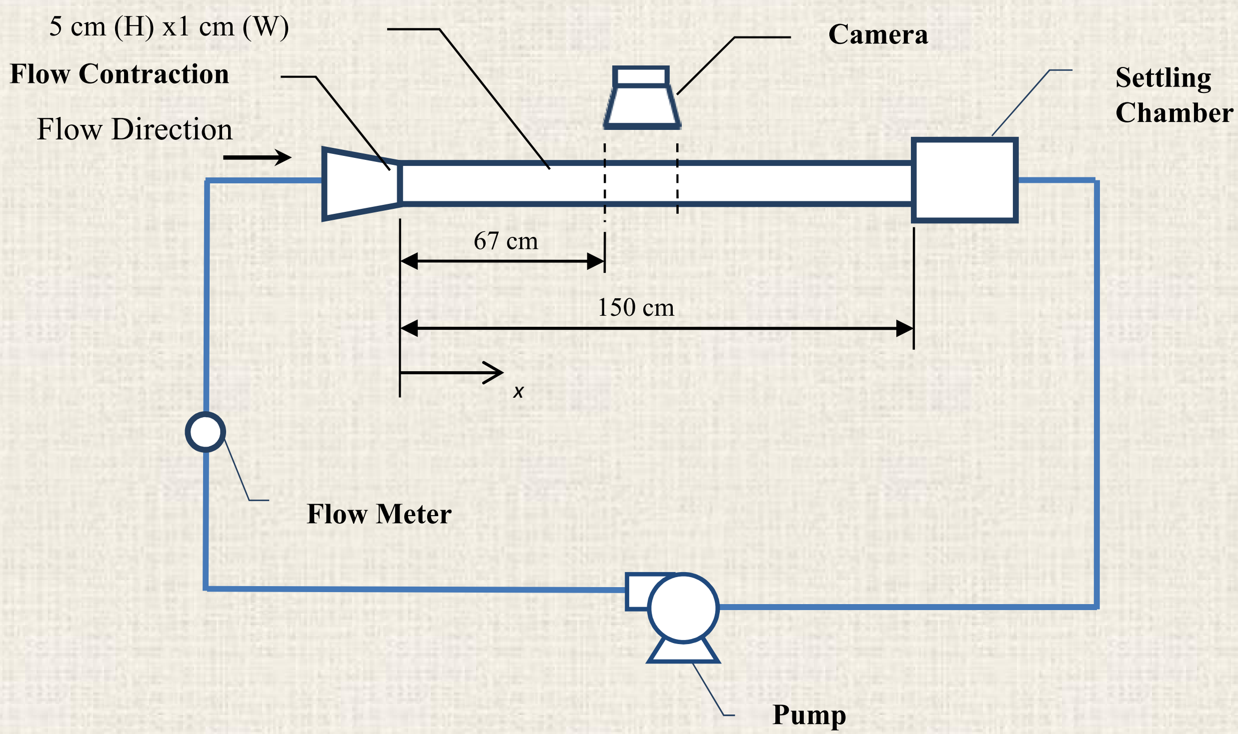
$$m_p \ddot{\mathbf{u}}_p = m_p \mathbf{f}_g + \sum_{c=1}^{N_c} \mathbf{f}_c + \mathbf{f}_{fluid}$$

Angular momentum

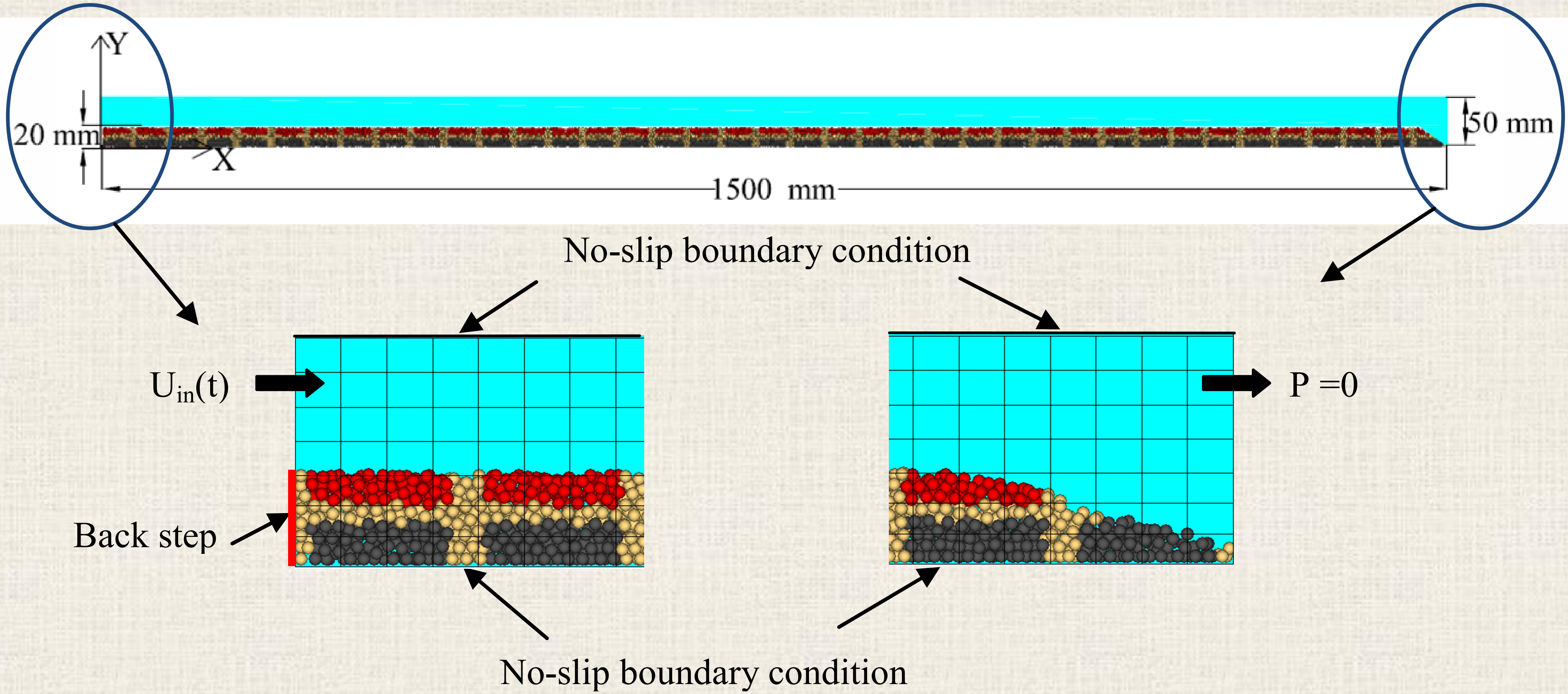
$$I_p \ddot{\boldsymbol{\theta}}_p = \sum_{c=1}^{N_c} \mathbf{r}_c \times \mathbf{f}_c$$

Experimental Setup

- Fluid velocity was obtained using *digital particle image velocimetry* (DPIV).
- The fluid used in the experiment was an aqueous solution of *sodium iodide* and *sodium thiosulfate*.
- The *sodium iodide* increases the refractive index of the solution to be nearly the same as the solid beads in order to measure the fluid velocity using DPIV technique.
- The *sodium thiosulfate* prevents discoloration of the solution.



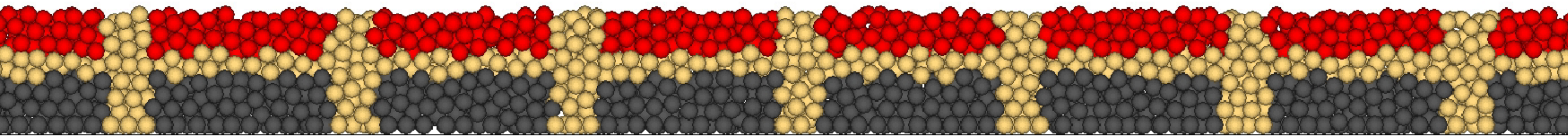
Numerical Simulation

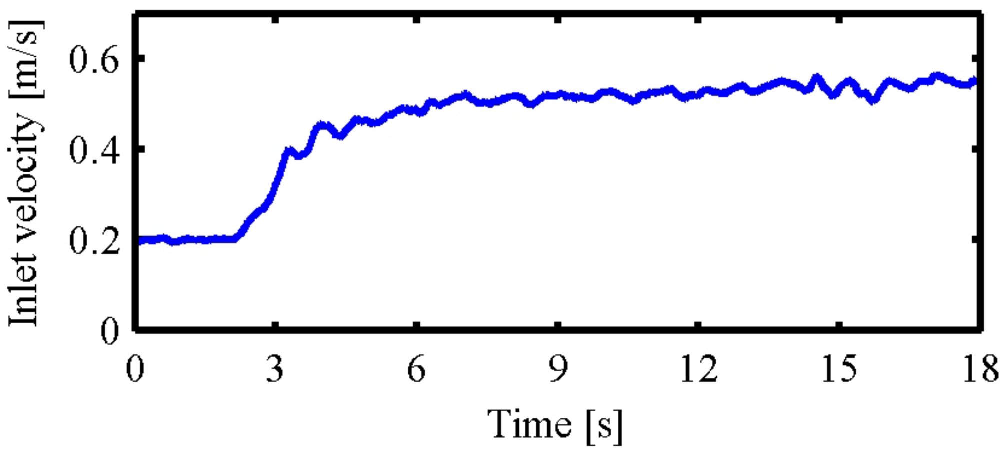


Simulation Data

Particles (Pyrex)	
Number	11639
Diameter	3 mm
Density	2230 kg/m^3
Normal Stiffness	1×10^5 N/m
Shear Stiffness	1×10^5 N/m
Friction Coefficient	0.5
Wall	
Normal Stiffness	1×10^5 N/m
Shear Stiffness	1×10^5 N/m
Friction Coefficient (side walls)	0.05
Friction Coefficient (base wall)	0.5
Fluid	
Density	1750 kg/m^3
Kinematic Viscosity	1.42×10^{-6} m^2/s

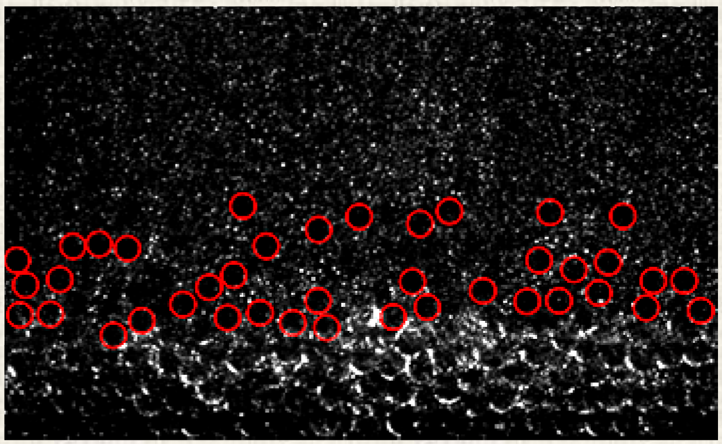
Particle Bed Erosion





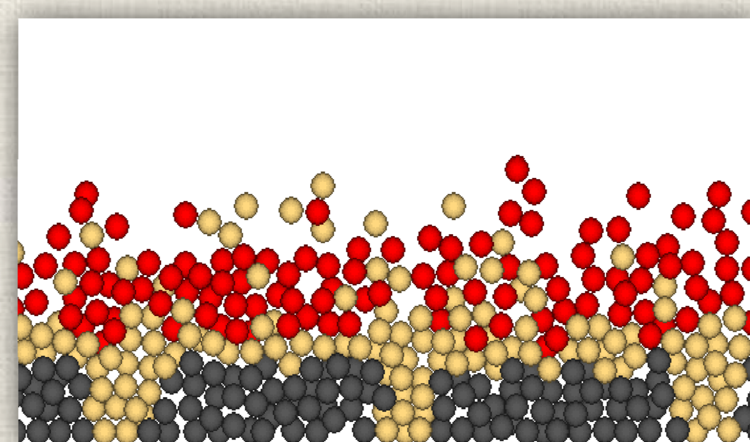
Particles Snapshots

Experimental

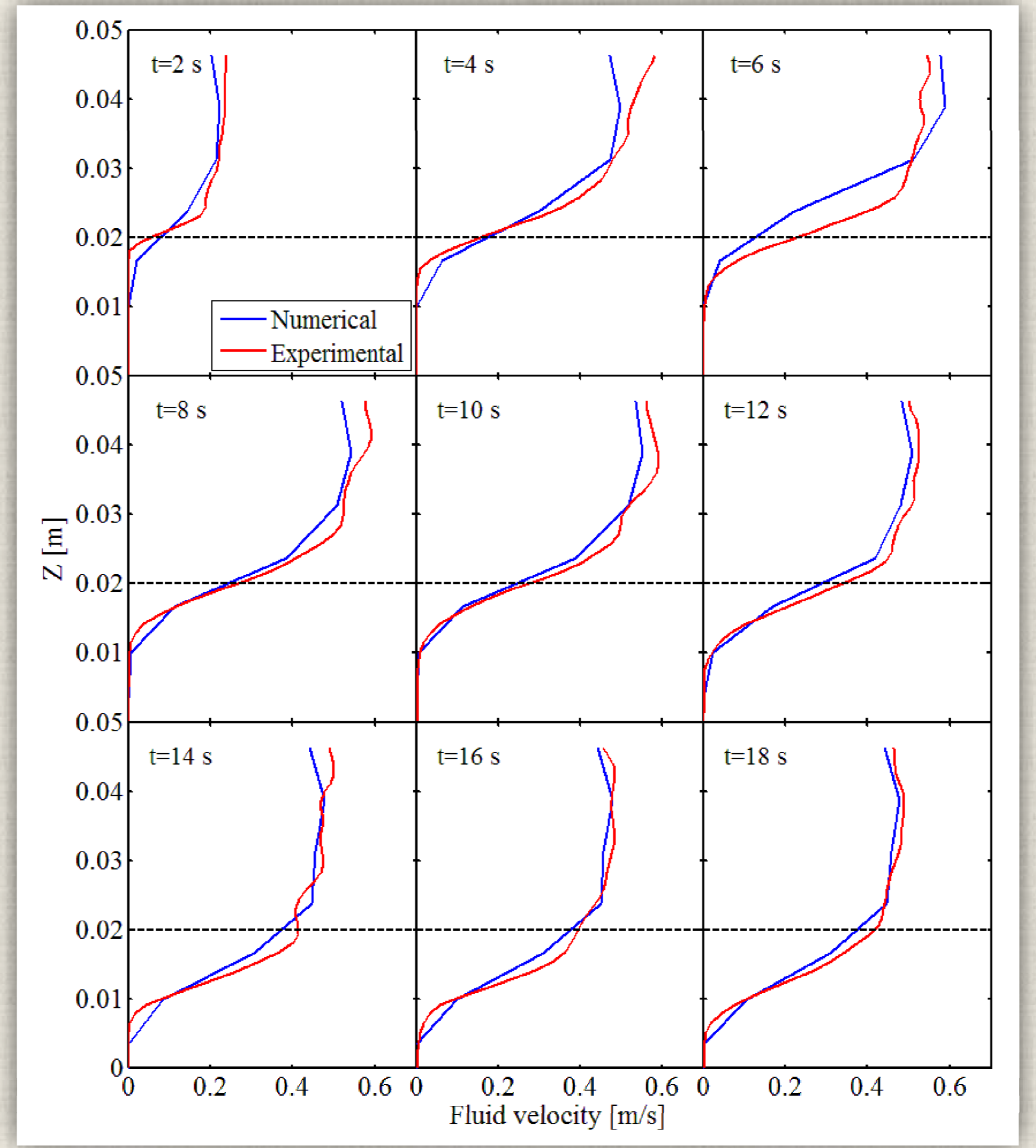


Particle bed

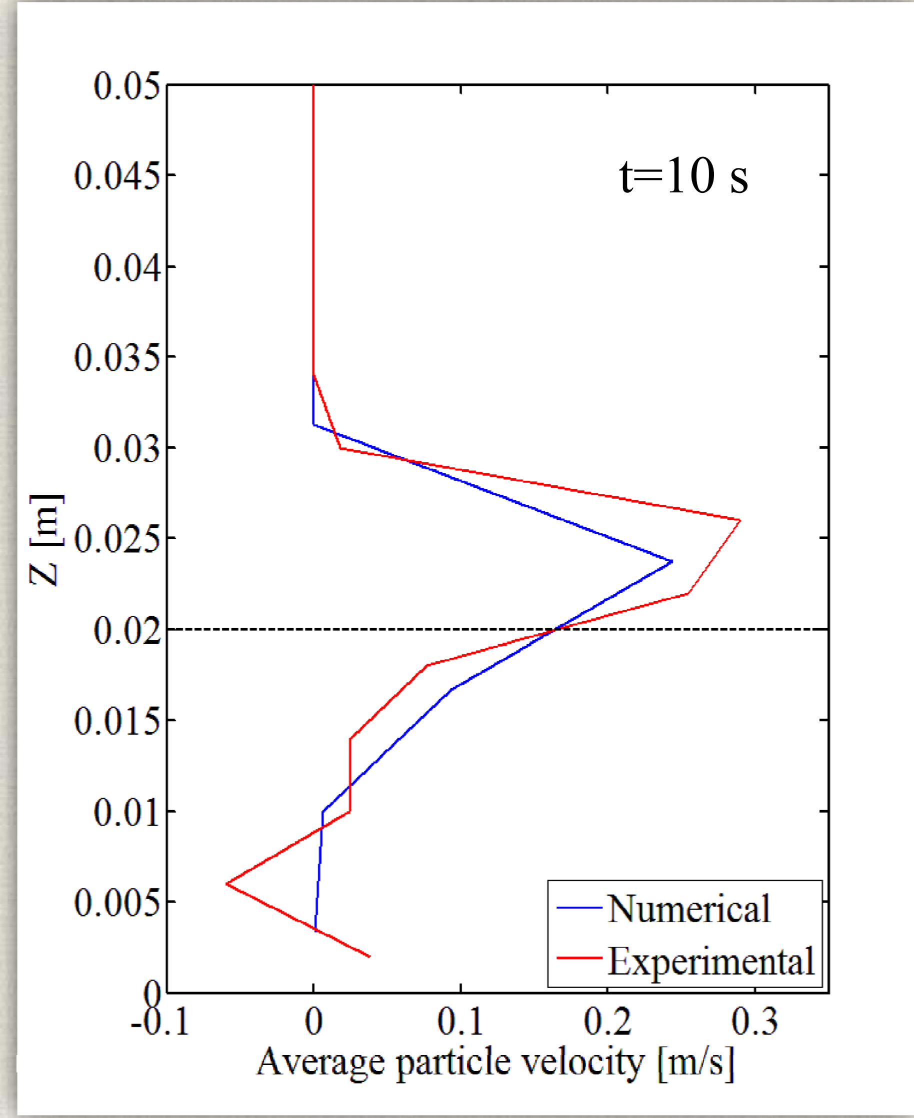
Numerical



Fluid Flow Velocity



Particles Velocity



Conclusions

- The dynamics of a particle bed subjected to flood-induced erosion was studied using a fully coupled numerical model.
- FEM was used to model the fluid and DEM was used to model the bed particles.
- An experimental program utilizing DPIV provided pore-scale fluid velocity.
- The numerical and experimental fluid and particle velocity profiles were in good agreement.
- The numerical and experimental results show that the fluid flow profile penetrates the bed for a small distance known as sheet flow layer.
- It is the relative velocity between the fluid penetrating the bed and the initially static particles that contributes to flow-induced drag and lift forces that cause particles to deform in response to these external forces.

Acknowledgement

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Questions?