Technische Universität Braunschweig

Modelling Wave-Structure-Soil Interaction with OpenFOAM®

Leichtweiss-Institute, Division of Hydromechanics, Coastal and Ocean Engineering, TU Braunschweig

Hisham Elsafti and Nils Goseberg, 27.03.2019

DANSIS OpenFOAM Seminar, Aalborg University Copenhagen, Denmark

Outline

- **Introduction**
- **The *geotechFoam* solver**
- **Modelling flow through porous media**
- **Concluding remarks and outlook**

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- The *geotechFoam* solver
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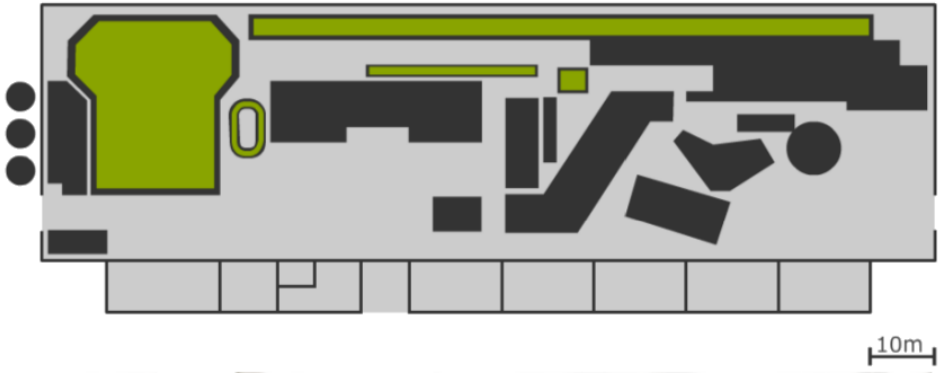
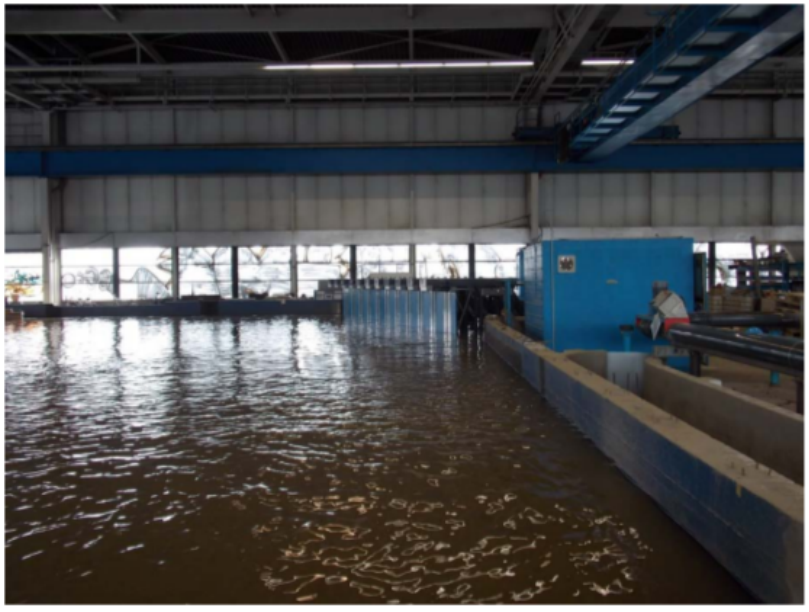
Facilities at LWI

- Lab area: 140m. X 40m.
- 3 wave flumes
- 3D wave basin
- www.tu-braunschweig.de/lwi



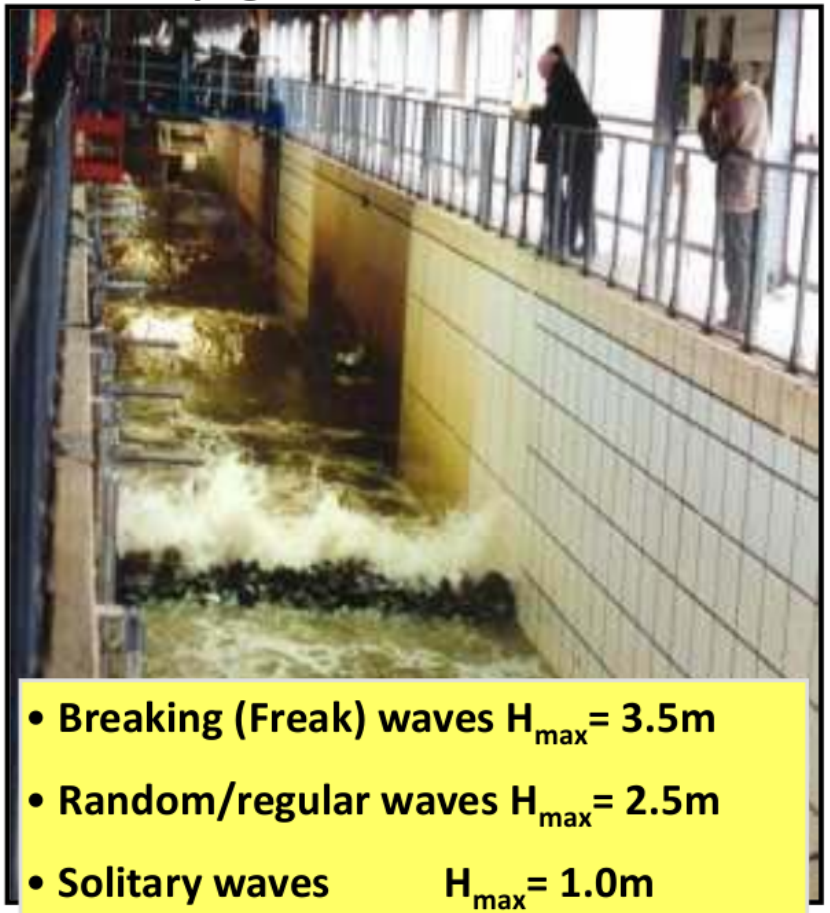


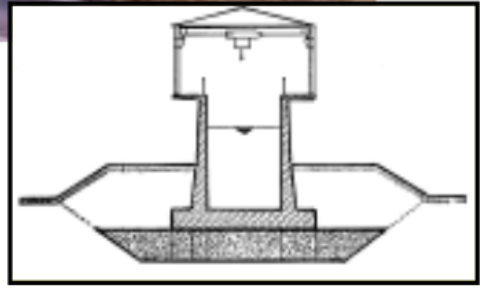
The Large-Wave Flume (GWK)

Coastal Research Centre

FZK
Joint Central Institution of University Hannover and TU Braunschweig

Homepage: www.fzk.uni-hannover.de





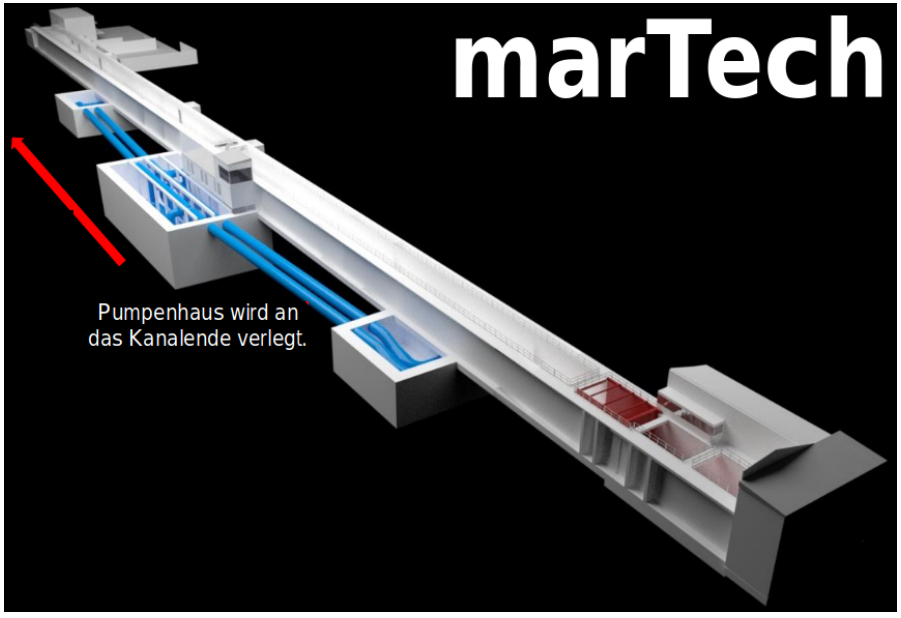
Dimensions

330m x 5m x 7m

- **Breaking (Freak) waves H_{max}= 3.5m**
- **Random/regular waves H_{max}= 2.5m**
- **Solitary waves H_{max}= 1.0m**

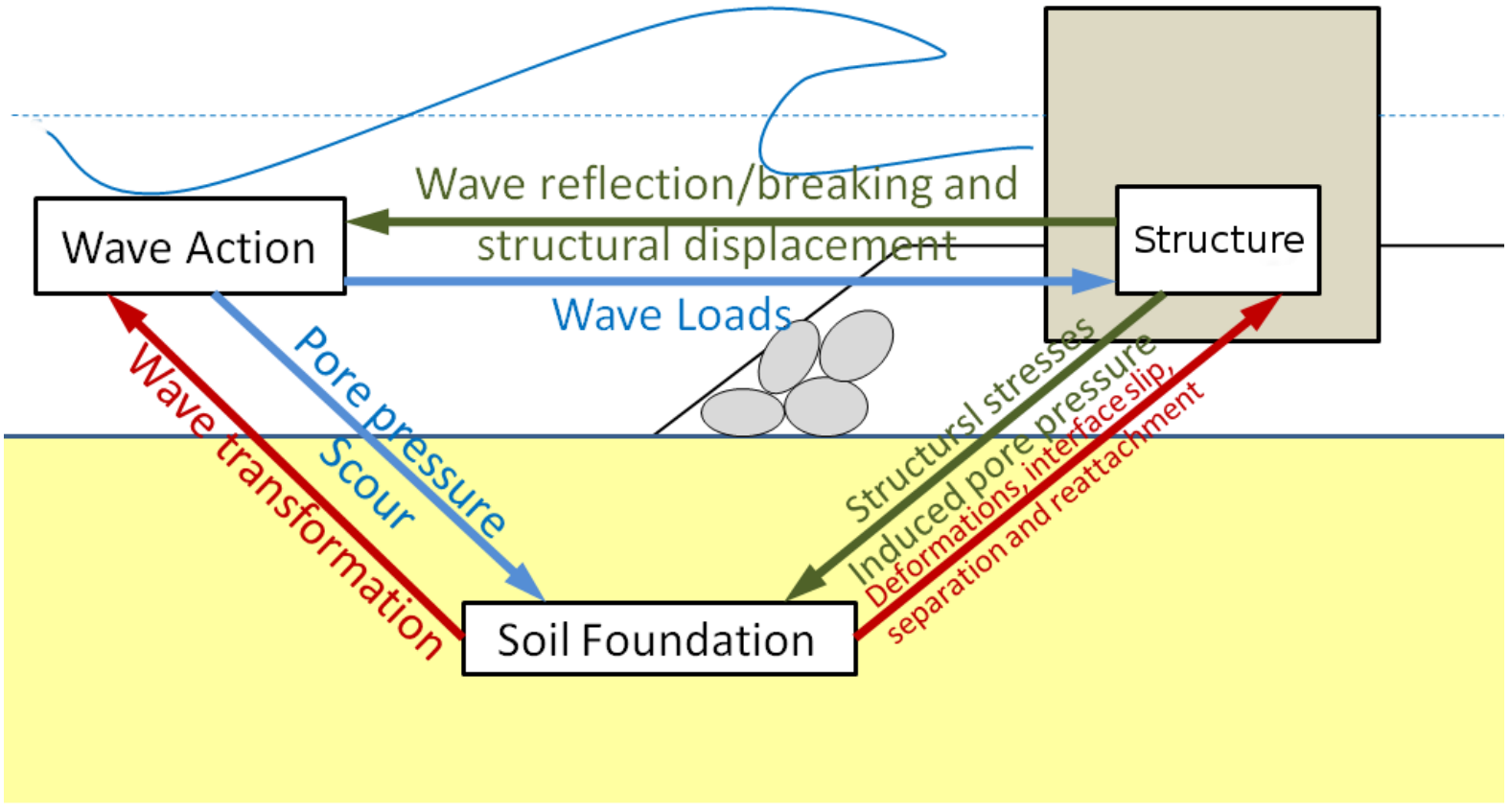
Extension of the GWK

- Financial support by **BMWi**: German Federal Ministry of Economy and Energy
- The *marTech* project: €35,526,200
- 4 years: 01.06.2017 until 30.5.2021
- New wave machine (maker)
- Introduction of curennts
- A deeper mid-section of the flume for including soil and foundations



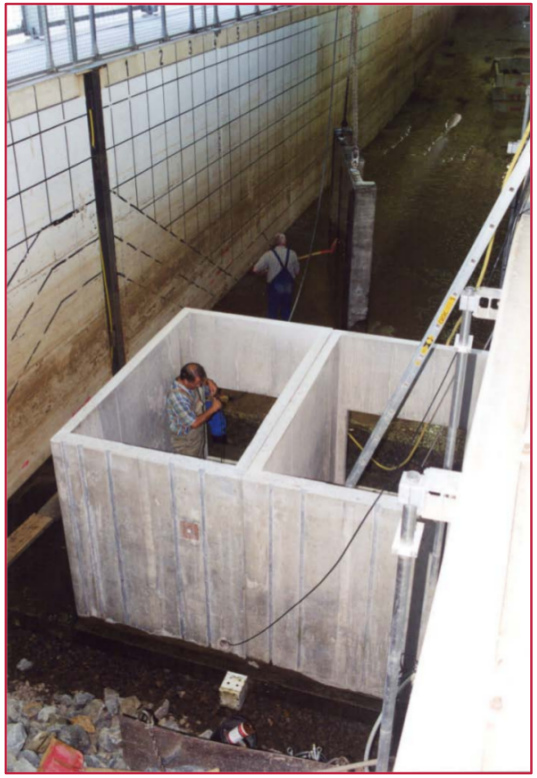
WaSFI concept

- The concept of wave-structure-foundation interaction



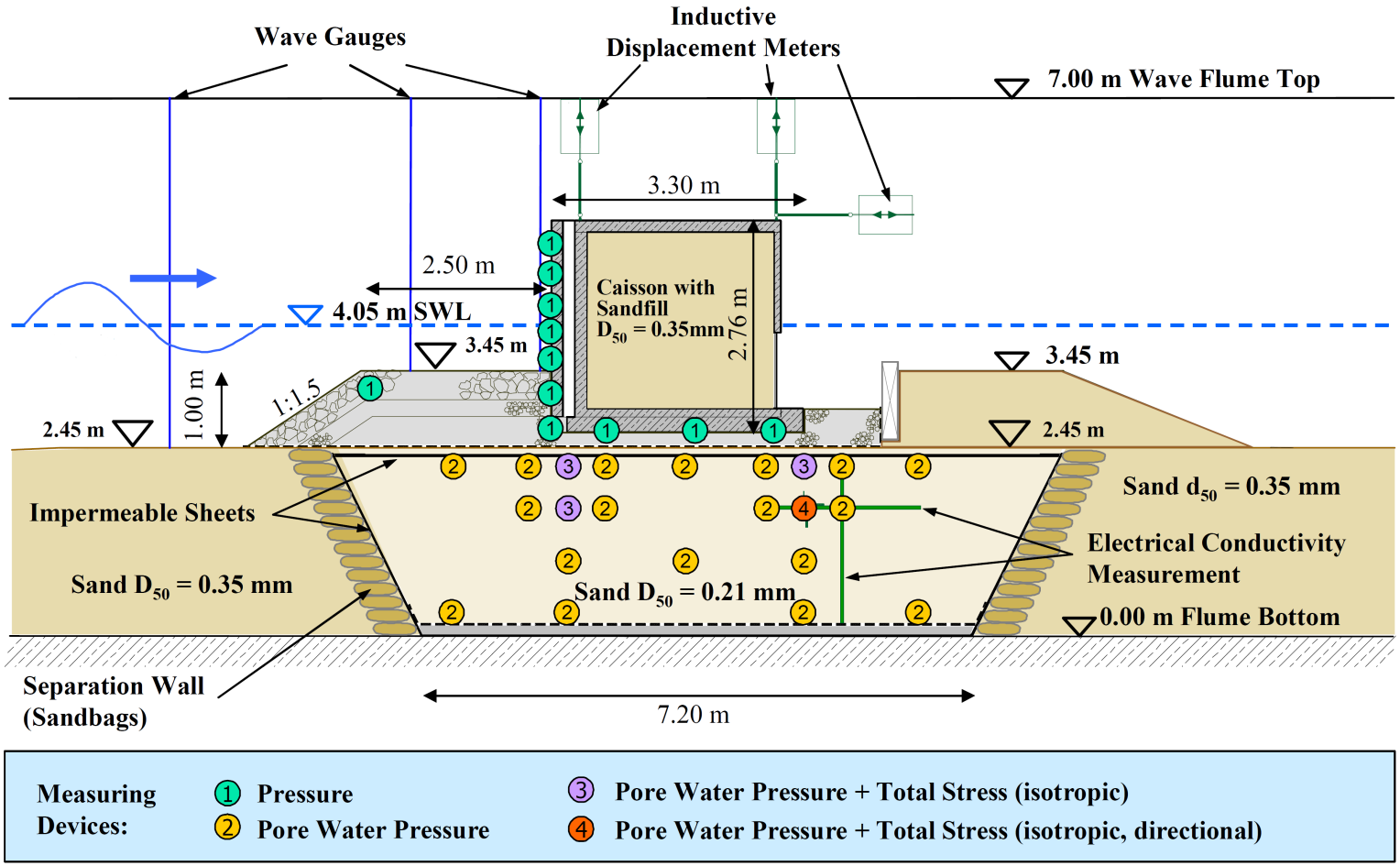
An example of WaSFI: Marine gravity structures

- The large wave flume (GWK), the coastal research center (FZK), Hanover



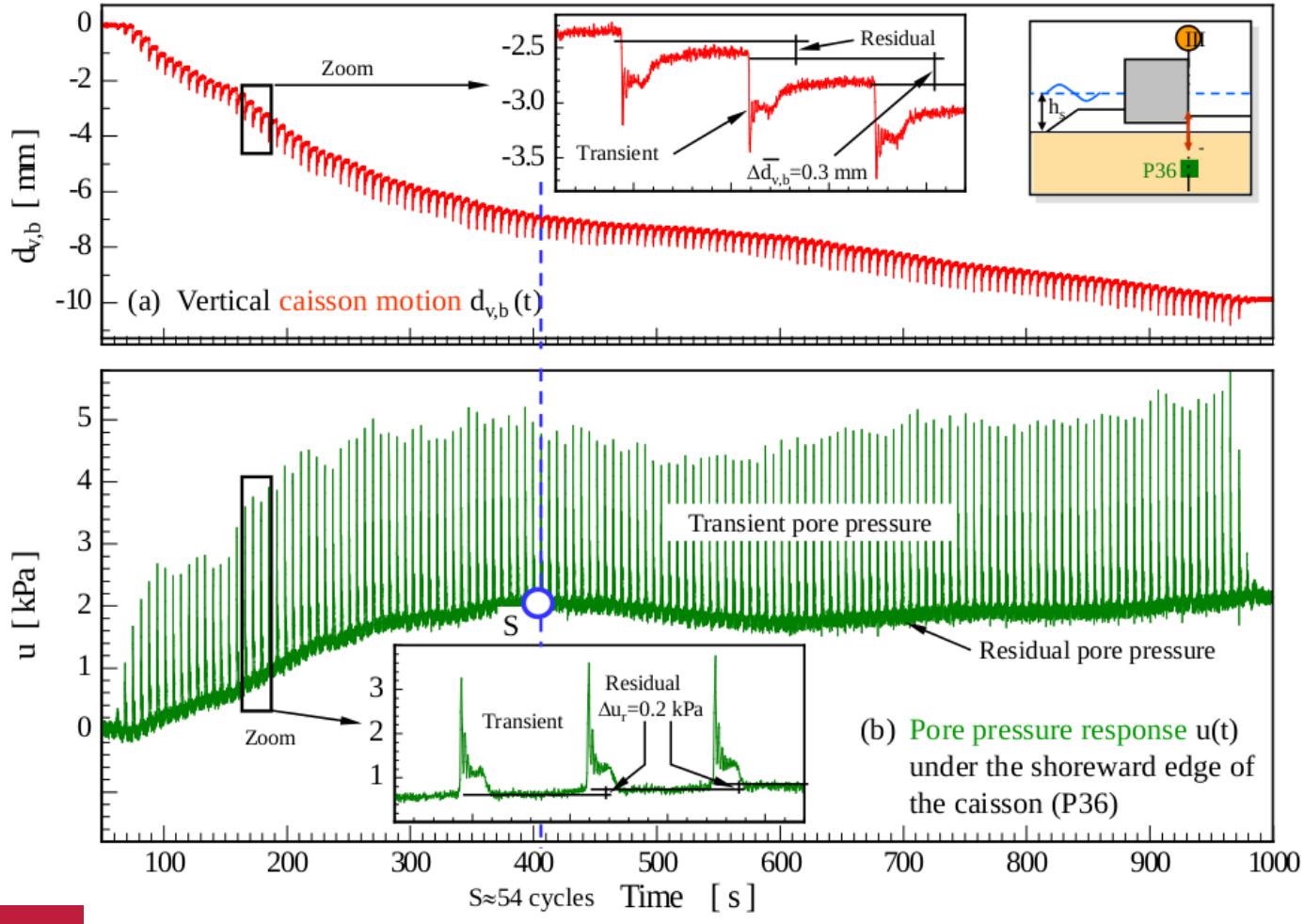
Caisson breakwater tests

- Oumeraci & Kudella, 2004



Displacement-pore pressure relationship

- Regular waves $H = 0.7m$, $T = 6.5s$ u. $h_s = 1.6m$



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The *geotechFoam* solver

- The Finite Volume Method (FVM)
- Solver of the fully-coupled fully-dynamic (extended) Biot equations
- An approximation is implemented by neglecting the pore fluid convective acceleration
- The $u - p$ approximation is also implemented (neglecting pore fluid acceleration completely)
- Different material zones: different material properties and/or models
- An interface for material models (no need to develop a new solver, possible import of developed material models from Abaqus, Flac, plaxis, OpenSees, etc.)
- A multi-surface plasticity model is implemented for simulating sand cyclic mobility
- Soil-structure interaction through frictional contact modelling
- A single pore fluid (water air mixture with a modified bulk modulus)

Extended Biot equations

The mixture momentum balance (equation of motion)

$$\nabla \cdot \boldsymbol{\sigma} - \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - c \frac{\partial \mathbf{u}}{\partial t} - \rho_f \left(\frac{\partial \overline{\mathbf{U}}}{\partial t} + \underline{\overline{\mathbf{U}} \cdot \nabla \overline{\mathbf{U}}} \right) + \rho \mathbf{b} = 0$$

The momentum balance of the pore fluid

$$\frac{\rho_f}{n} \left(\frac{\partial \overline{\mathbf{U}}}{\partial t} + \underline{\overline{\mathbf{U}} \cdot \nabla \overline{\mathbf{U}}} \right) = -\nabla p - \rho_f \frac{\partial^2 u}{\partial t^2} + \rho_f \mathbf{b} - \mathbf{S}$$

The mass balance equation of the pore fluid

$$\nabla \cdot \overline{\mathbf{U}} + \frac{\partial \varepsilon_v}{\partial t} + \frac{1}{Q} \frac{\partial p}{\partial t} = 0$$

The $u - p$ approximation

The mixture momentum balance (equation of motion)

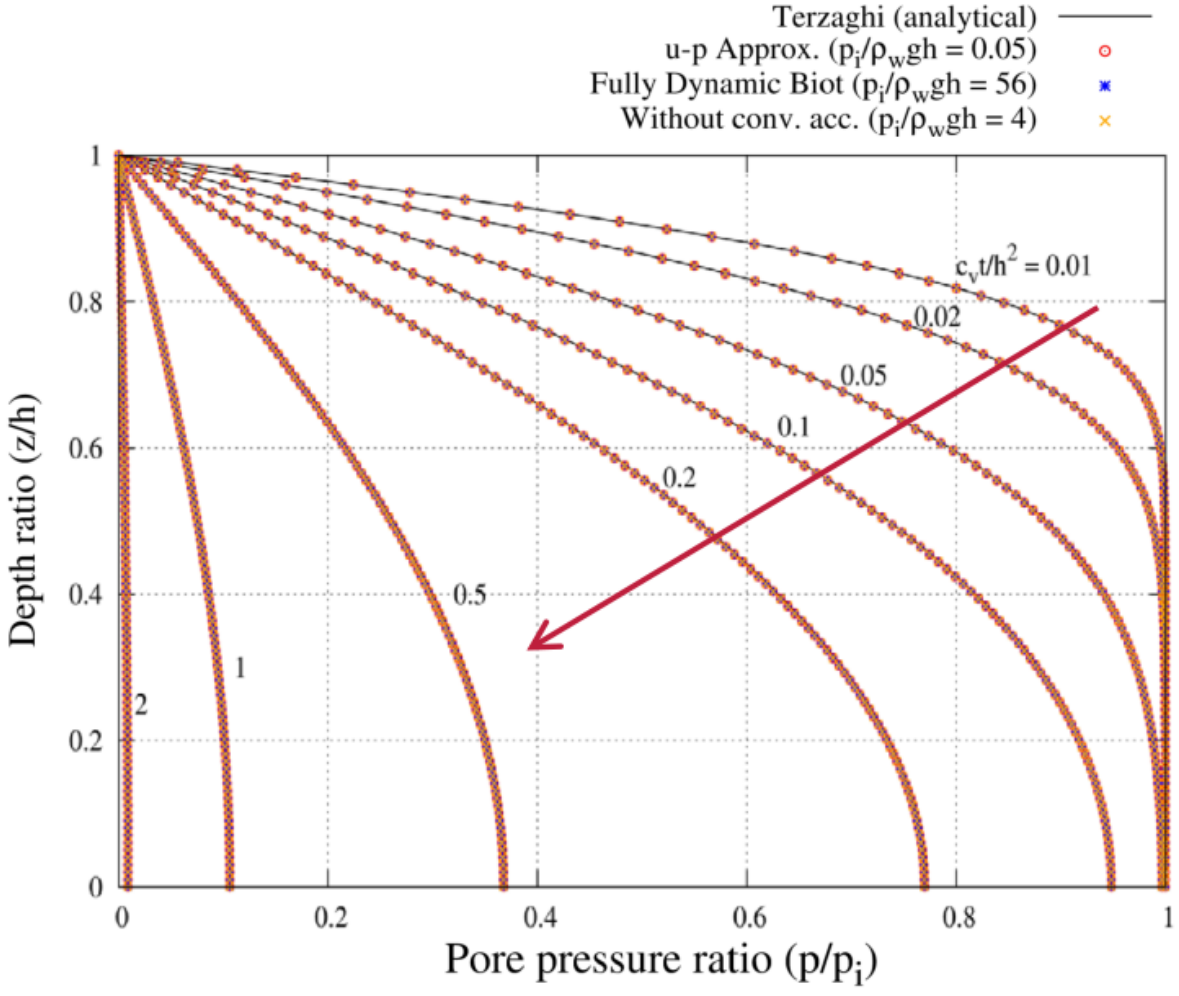
$$\nabla \cdot \boldsymbol{\sigma} - \rho \frac{\partial^2 \mathbf{u}}{\partial t^2} - c \frac{\partial \mathbf{u}}{\partial t} + \rho \mathbf{b} = 0$$

The pore fluid mass and ~~momentum~~ balance

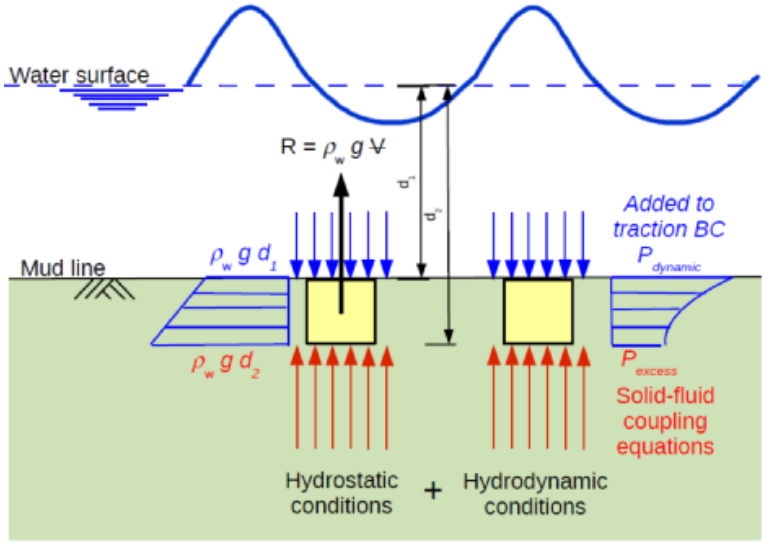
$$\nabla \cdot \left(\frac{k}{\rho_f g} \left(-\nabla p - \rho_f \frac{\partial^2 \mathbf{u}}{\partial t^2} + \rho_f \mathbf{b} \right) \right) + \frac{\partial \varepsilon_v}{\partial t} + \frac{1}{Q} \frac{\partial p}{\partial t} = 0$$

1D consolidation (Terzaghi)

Consolidation		
u_z	p	$\overline{\mathbf{U}}_z$
$T_z = p_i$	$p = 0$	$\frac{\partial \overline{\mathbf{U}}_z}{\partial z} = 0$
Initial conditions		
$p = \frac{p_i}{1+\frac{n}{K_f m_v}}$		
$u_z = 0$	$\frac{\partial p}{\partial z} = 0$	$\overline{\mathbf{U}}_z = 0$

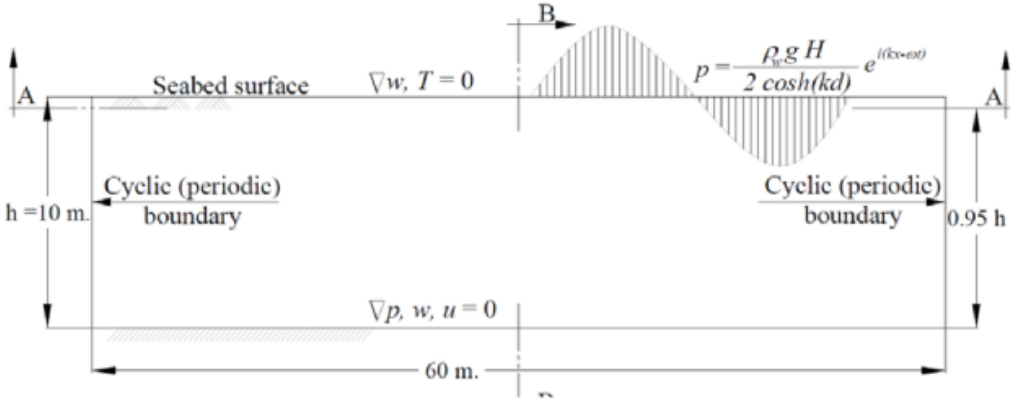


Wave-induced direct seabed response

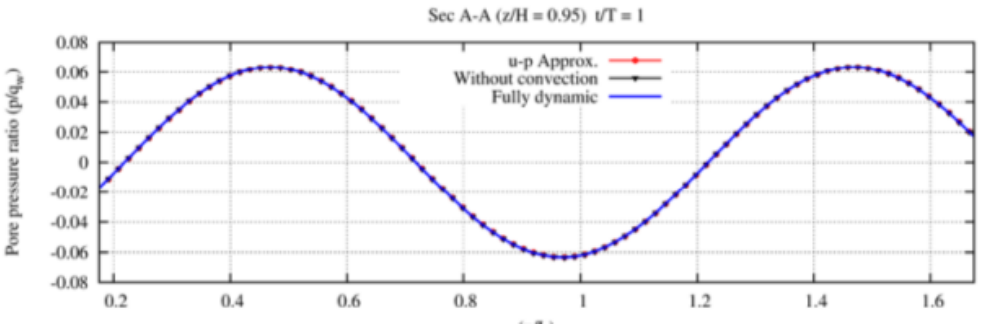


Linear wave theory – Cyclic boundaries –

Top/bottom boundaries

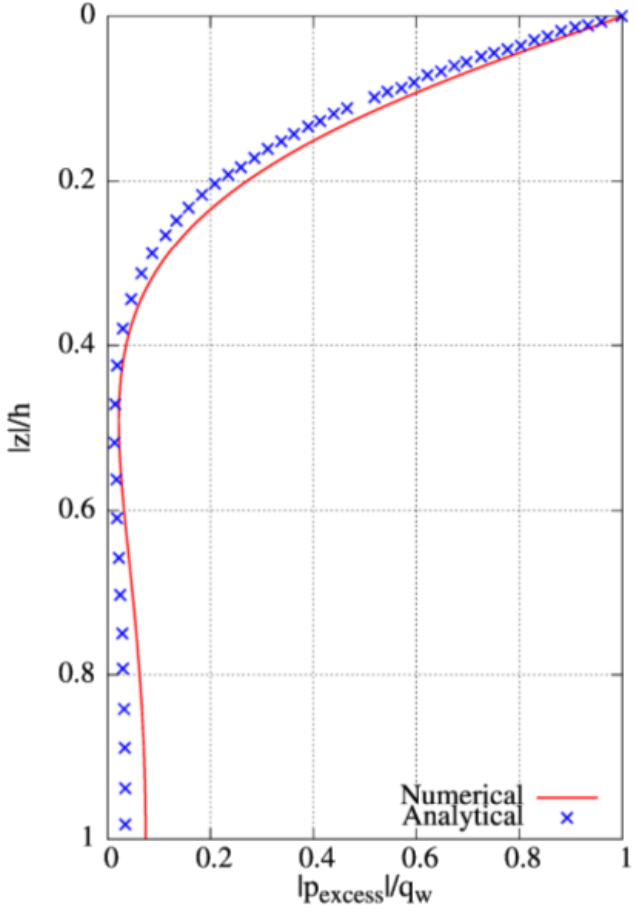


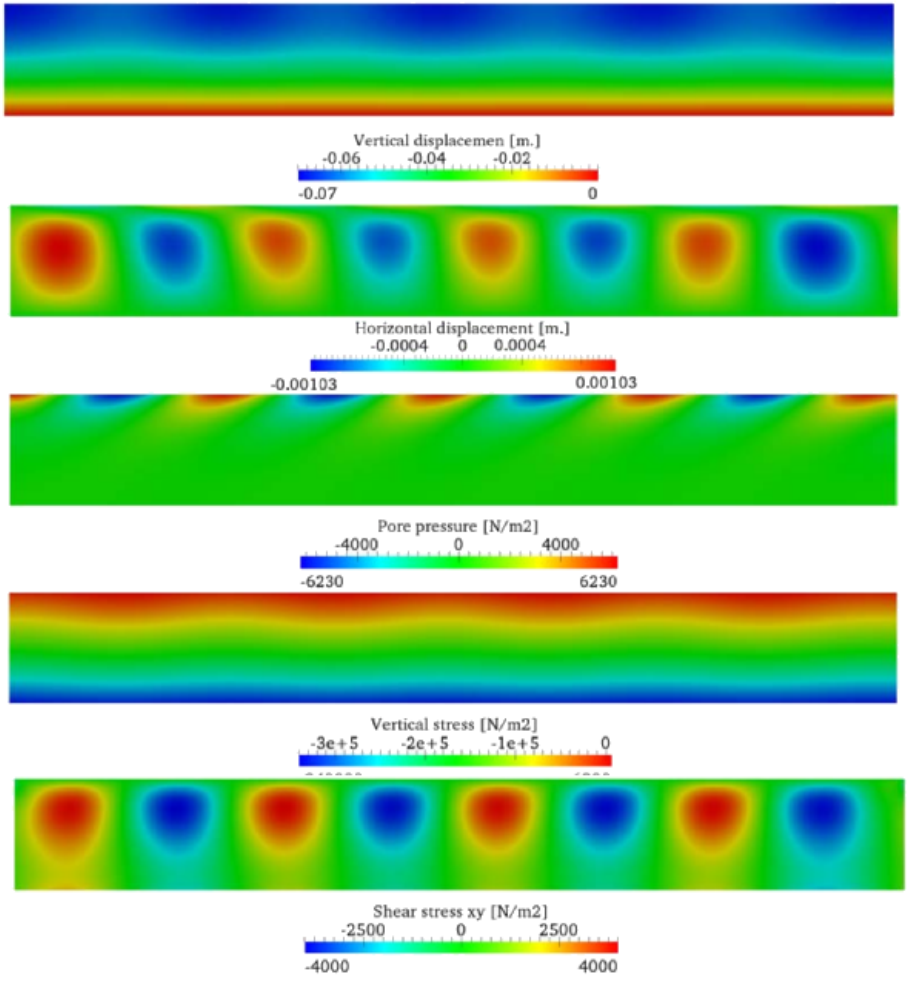
Wave height (H)	1 m.
Wave length (L)	34.907 m.
Wave period (T)	5 s.
Water depth (d_w)	8 m.
Wave steepness. (H/L)	0.0286
Ratio of water depth to wave length ($d_w L$)	0.2292



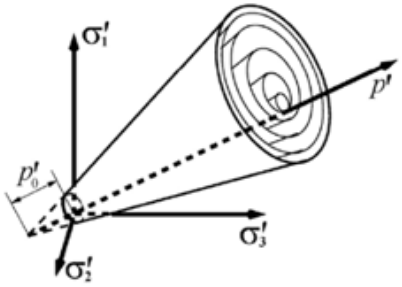
Wave-induced seabed response (validation)

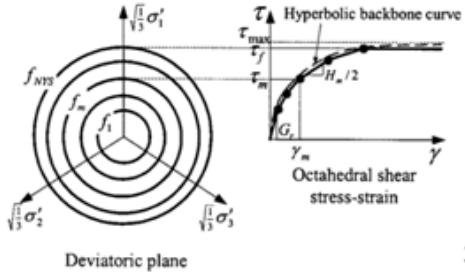
Jeng (1996)



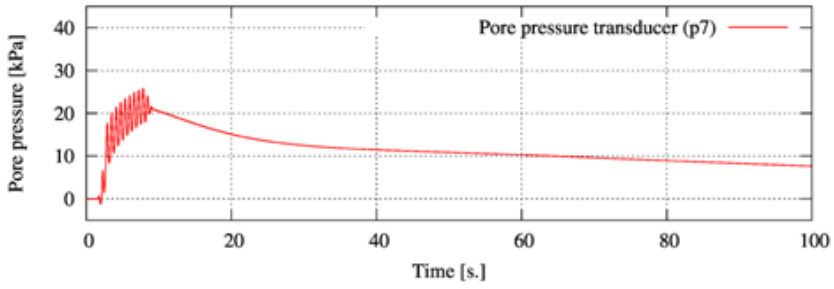


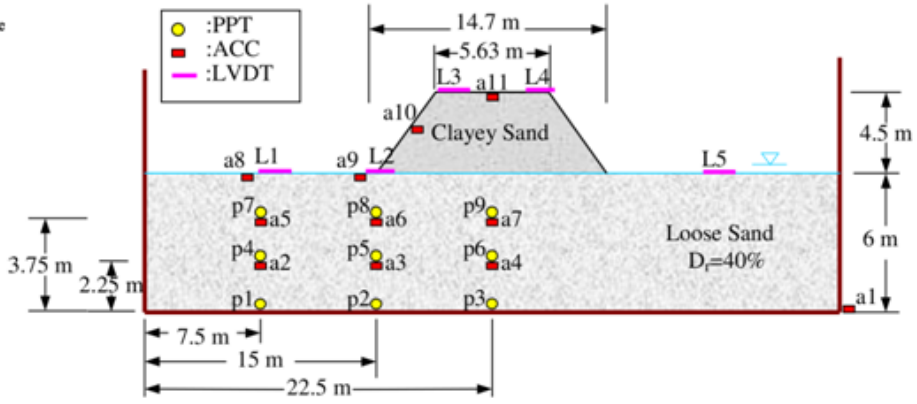
Seismic-induced response of an embankment

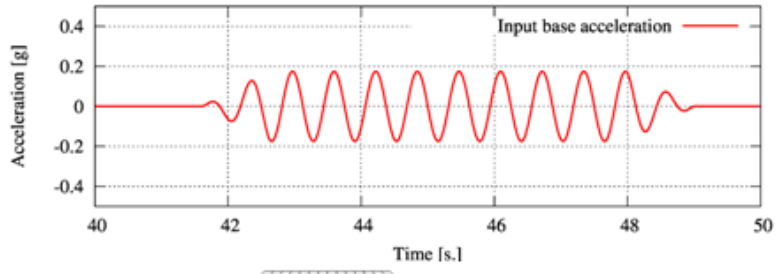




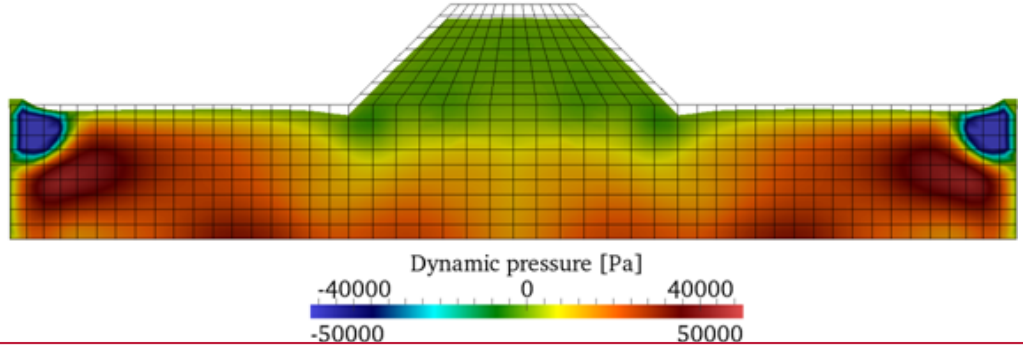
Drucker-Prager criterion (Elgamal et al., 2003)





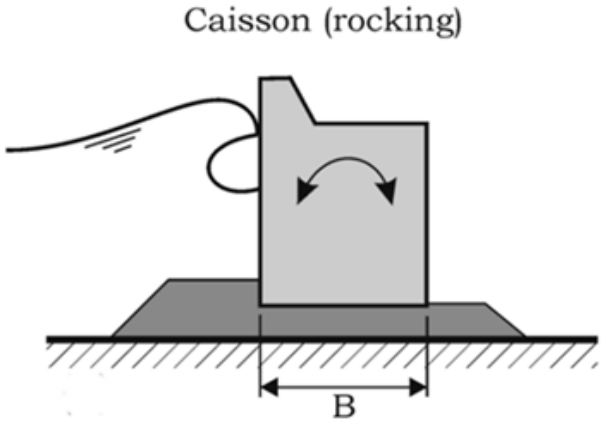


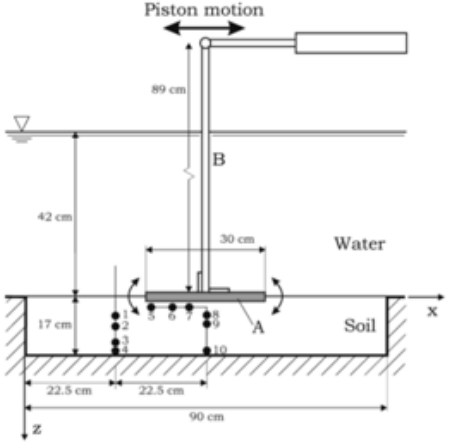
- Centrifuge tests (Elgamal et al., 2007)
- Residual pore pressure build up and dissipation

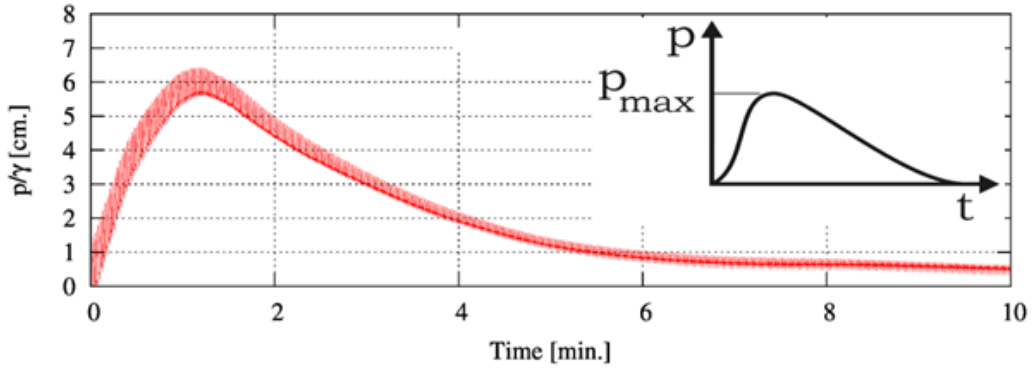


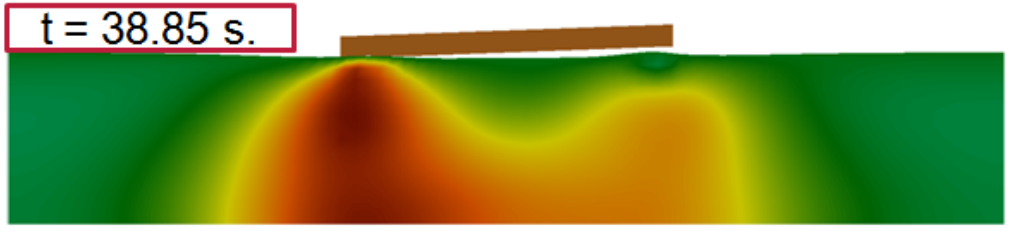
Rocking motion of a plate on seabed

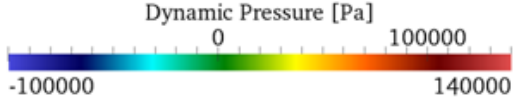
Sumer et al. (2008)



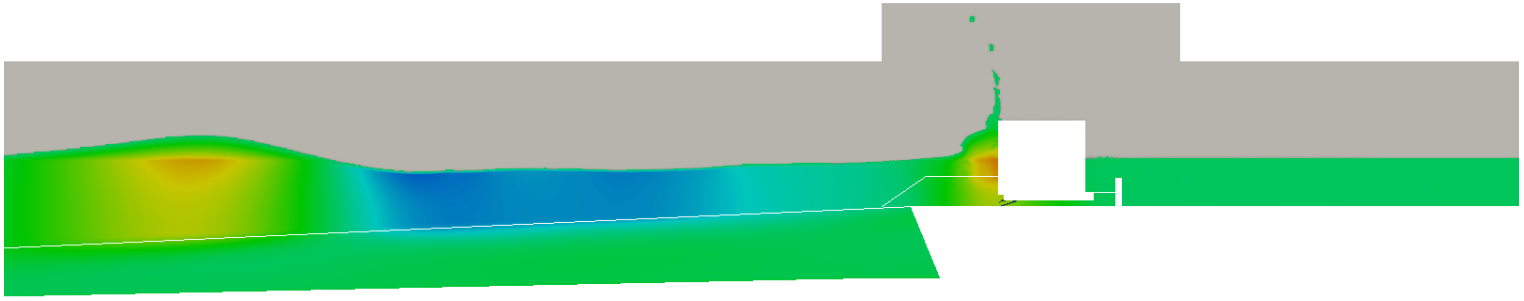


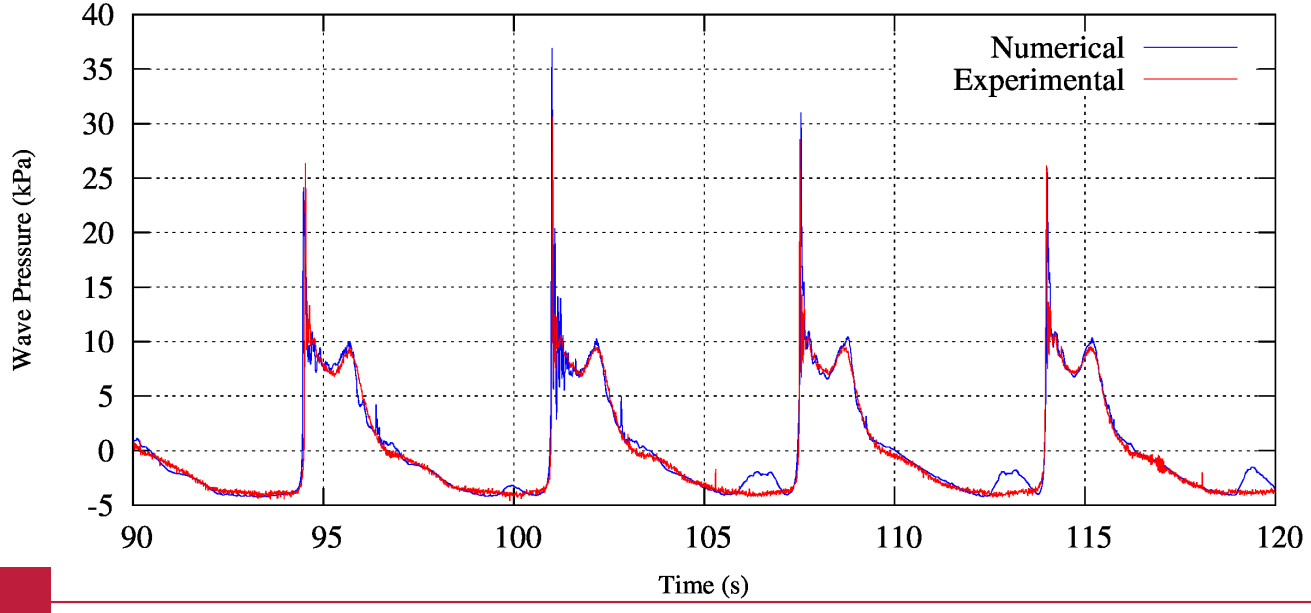




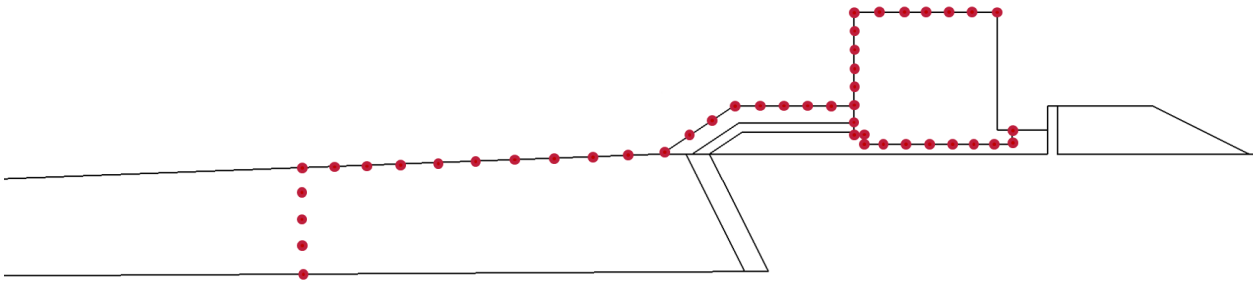


Breaking wave impact on a caisson breakwater

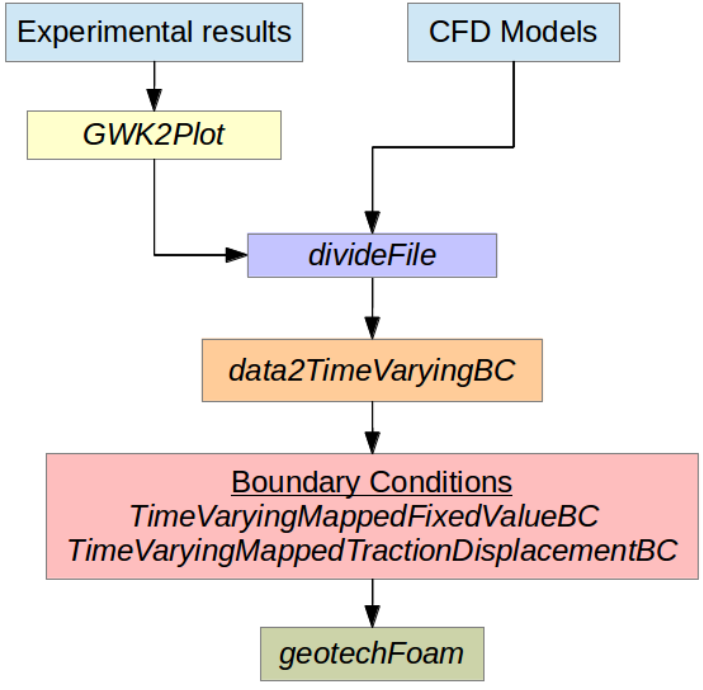




One-way coupling (caisson breakwater)

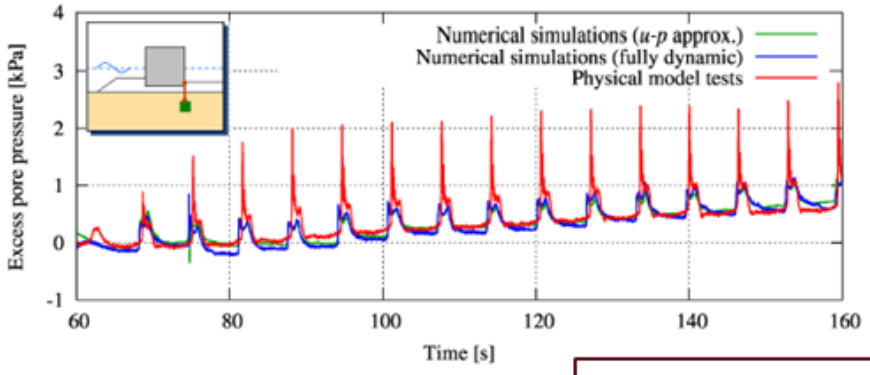


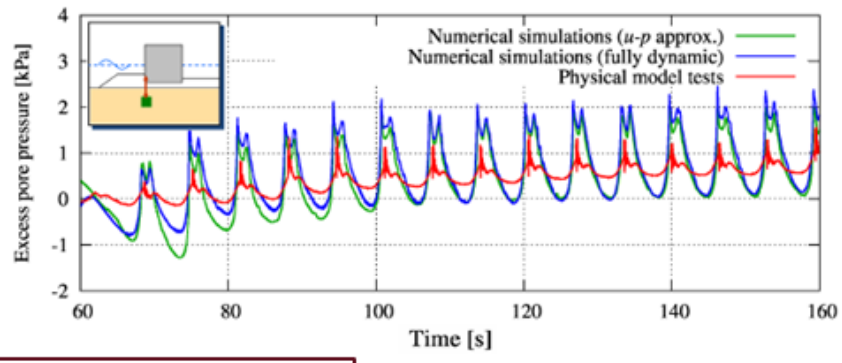
- One way (semi-) coupling
- Separate time and space discretisation
- Can also be used to introduce input from experimental results
- Overlap zones of CFD and CSD solvers for realistic flow through porous media



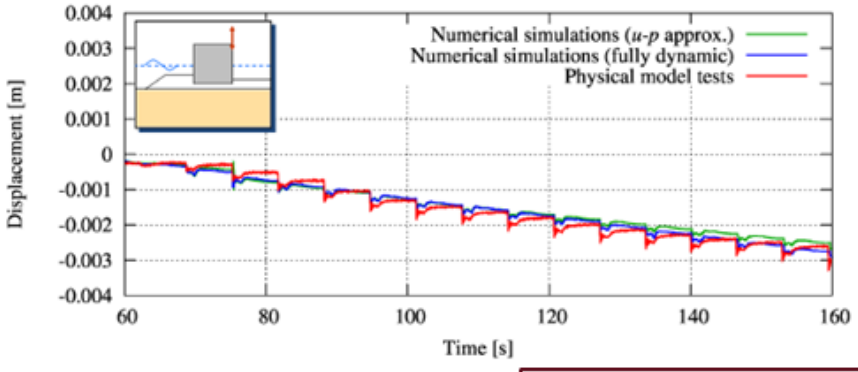
One-way (semi) coupling validation

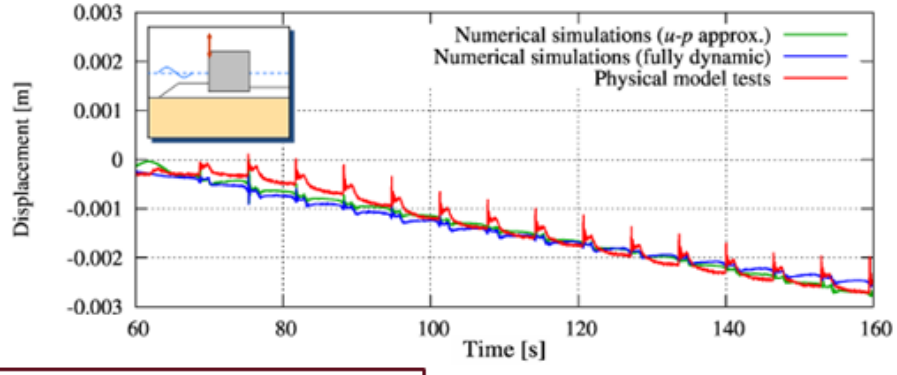
Regular Breaking Waves: H=0.7m, T=6.5s





Pore pressure underneath caisson





Displacement at top edges of caisson

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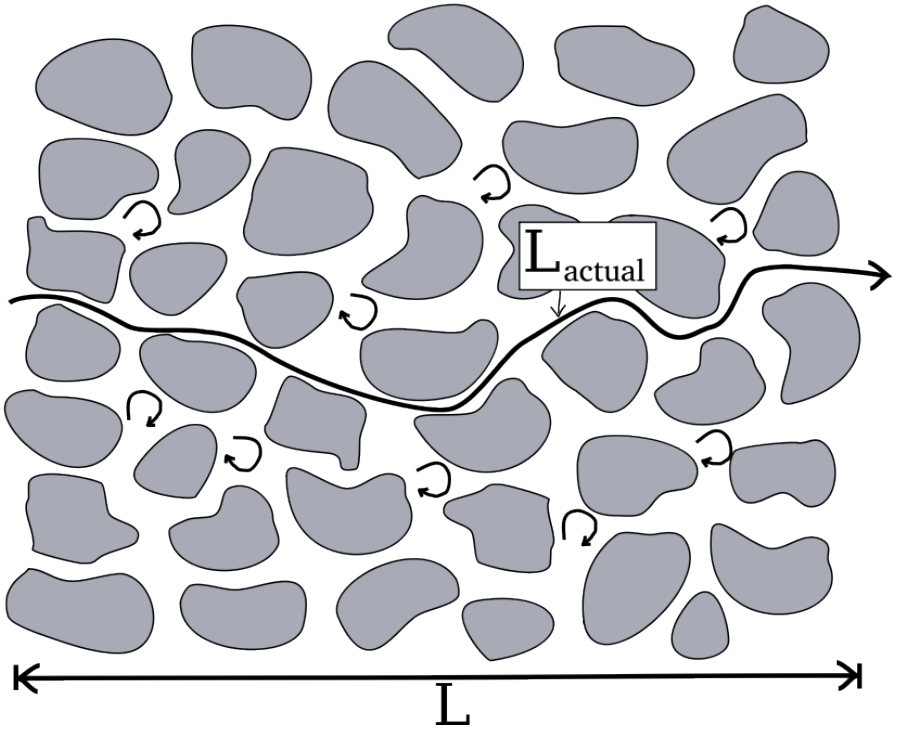
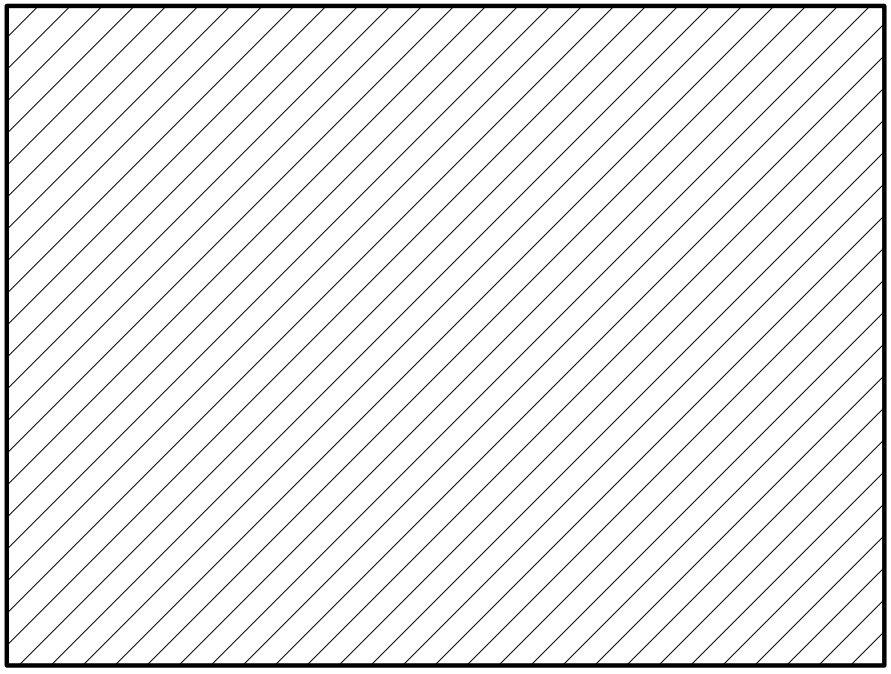
Water flow through granular materials



- Resolved solid particles
- Flow modelled more accurately
- More difficult, more expensive



- Averaged domain
- Flow meets resistance
- More convenient, much faster

Averaged models of granular materials

- Resistance to flow: drag force + inertial force
- Drag force: resistance to unidirectional flow (velocity constant)
- Inertial force: resistance to transient flow (velocity changes)
- Further, drag force: linear component (Darcy) + nonlinear component (Forchheimer)
- More elaborate models: e.g. Lin and Karunarathna (2007)
- Darcy (simplest drag model):

$$\overline{\mathbf{U}} = -\mathbf{K}I$$

Drag resistance

- Drag resistance force (sink term):

$$\mathbf{F_d} = -\nabla p = -\rho g I$$

- Linear model (Darcy):

$$\mathbf{F_d} = \rho g \frac{\overline{\mathbf{U}}}{\mathbf{K}} = \rho g \frac{\overline{U}}{K} \text{ –> isotropic}$$

- Nonlinear model (Darcy-Forchheimer):

$$\mathbf{F_d} = \rho g (a\overline{U} + b\overline{U}\left|\overline{U}\right|)$$

- Nonlinear model (Lin and Karunarathna, 2007):

$$\mathbf{F_d} = \rho g (a\overline{U} + c\overline{U}\sqrt{\left|\overline{U}\right|} + b\overline{U}\left|\overline{U}\right|)$$

New proposed drag model

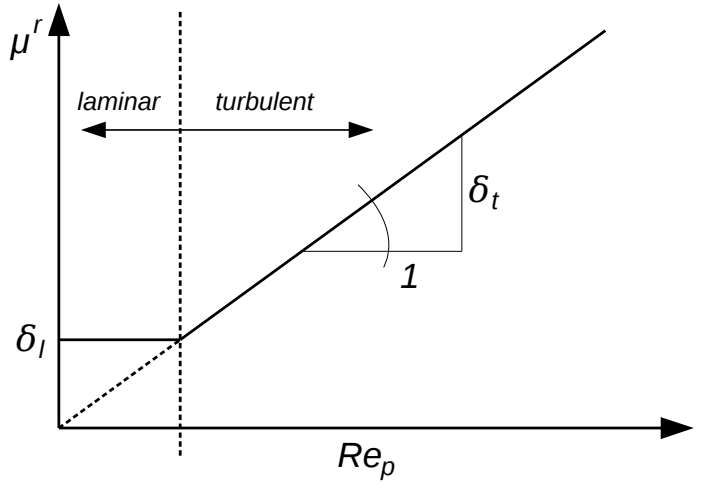
- Based on the concept of *effective viscosity*
- Effective viscosity is a concept used for turbulence modelling (eddy viscosity)
- An artificial (higher) viscosity is given to water to model resistance
- The drag force (simplified):

$$\mathbf{F_d} = \nabla \cdot \tau_{\text{(porous drag)}}$$

$$\mathbf{F_d} = \mu^{eff}((\nabla\overline{\mathbf{U}} + (\nabla\overline{\mathbf{U}})^T) - \frac{2}{3}(\nabla \cdot \overline{\mathbf{U}})\mathbf{I})$$

$$\mu^{eff} = \max\left[\delta_l, \delta_t Re_P\right] \mu_{water}$$

- New parameters:
  - δ_l: linear drag parameter
  - δ_t: nonlinear drag parameter
  - Re_P: Particles Re
- Drag is either linear or nonlinear



Inertial resistance model

- Inertial resistance force: with added mass coefficient (c_A)

$$F_i = c_A \frac{\partial \overline{U}}{\partial t}$$

$$c_A = \gamma \frac{(1-n)}{n}$$

- Typically in porous flow models $\gamma = 0.34$
- Van Gent et al. (1995):

$$\gamma = \max\left(0.85 - 0.015\frac{ngT}{A_{\overline{U}}}, 0\right)$$

$$b = 1.1\left(1 + \frac{7.5}{KC}\right)\frac{1-n}{n^3}\frac{1}{nD_{50}} \quad \text{where:} \quad KC = \frac{A_{\overline{U}}T}{nD_{50}}$$

- T and $A_{\overline{U}}$ are period and amplitude of oscillatory flow
- Van Gent's model cannot be generalized to transient flow

New fluid momentum balance equations

- Applying VAT and adding pore fluid viscous stresses, added viscous stresses due to turbulence, sink term for drag resistance and inertial resistance

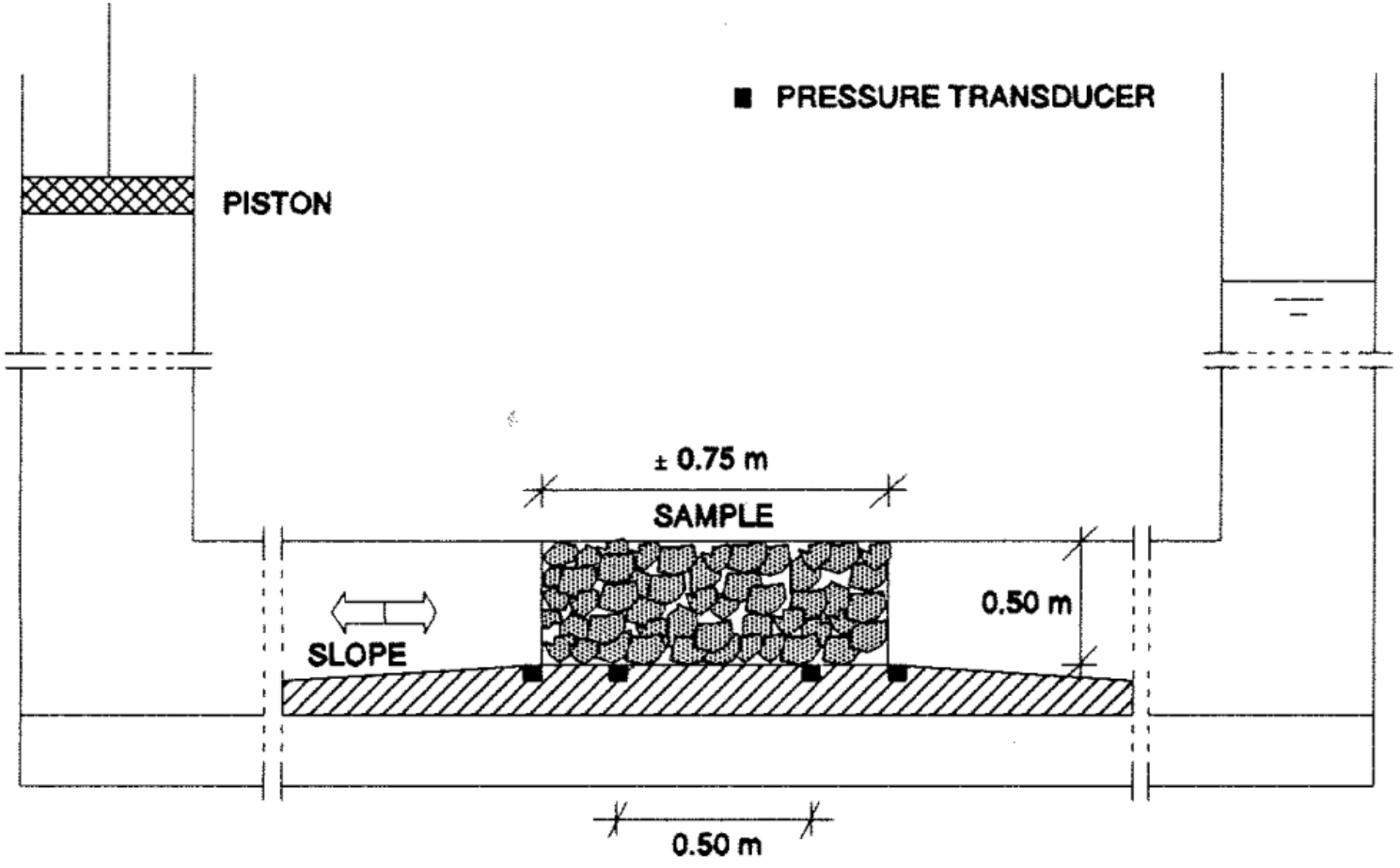
$$\rho_f \left(\frac{(1+c_A)}{n} \frac{\partial \overline{\mathbf{U}}}{\partial t} + \frac{1}{n^2} \overline{\mathbf{U}} \cdot \nabla \overline{\mathbf{U}} \right) = -\nabla p + \frac{1}{n} \left(\nabla \cdot \left(\overline{\boldsymbol{\tau}} + \frac{\overline{\mathbf{R}}}{n} \right) \right) - \rho_f \frac{\partial^2 u}{\partial t^2} + \rho_f \mathbf{b} - \mathbf{S}$$

- Viscosity ratio μ^r to represent effective viscosity (new model)

$$\rho_f \left(\frac{(1+c_A)}{n} \frac{\partial \overline{\mathbf{U}}}{\partial t} + \frac{1}{n^2} \overline{\mathbf{U}} \cdot \nabla \overline{\mathbf{U}} \right) = -\nabla p + \frac{\mu^r}{n} \left(\nabla \cdot \left(\overline{\boldsymbol{\tau}} + \frac{\overline{\mathbf{R}}}{n} \right) \right) - \rho_f \frac{\partial^2 u}{\partial t^2} + \rho_f \mathbf{b}$$

where: $\mu_r = \dfrac{\mu^{eff}}{(\mu + \overline{\mu}_t)} > 1$

Van Gent (1993) physical model tests



Recalibration of van Gent's model

- For a –> 1732 instead of 1000

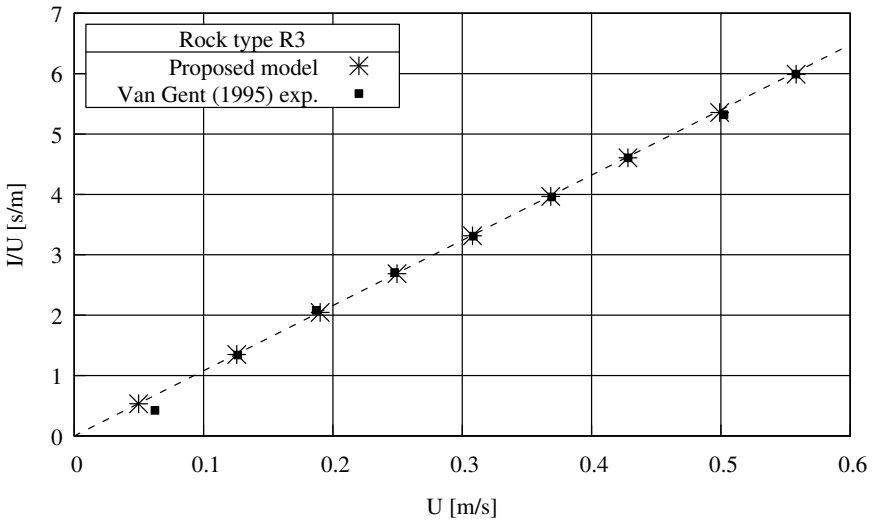
$$a = 1732 \frac{(1-n)^2}{n^3} \frac{\nu}{g D_{50}^2}$$

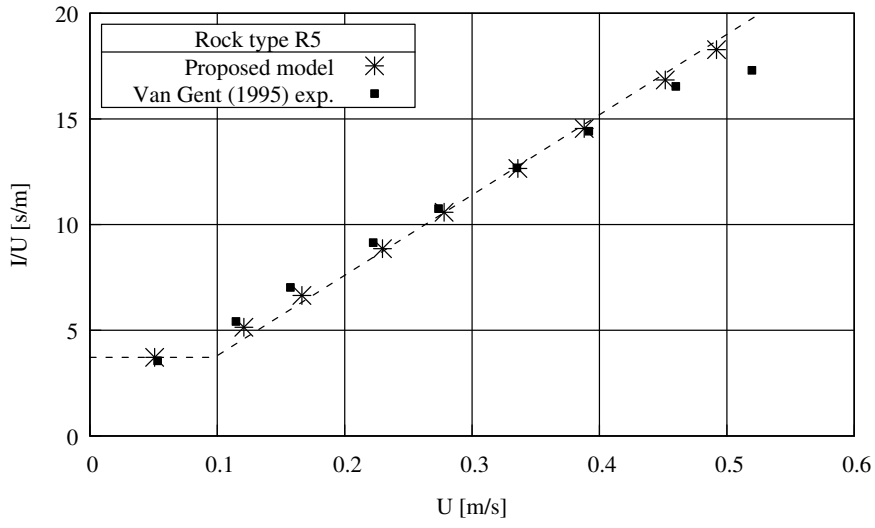
- For b –> 0.665 instead of 1.1

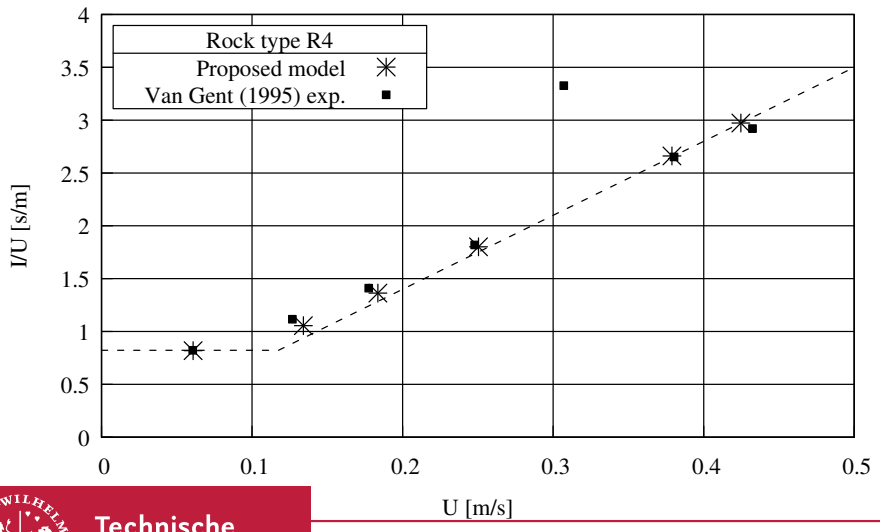
$$b = 0.665 \frac{1-n}{n^3} \frac{1}{g D_{50}}$$

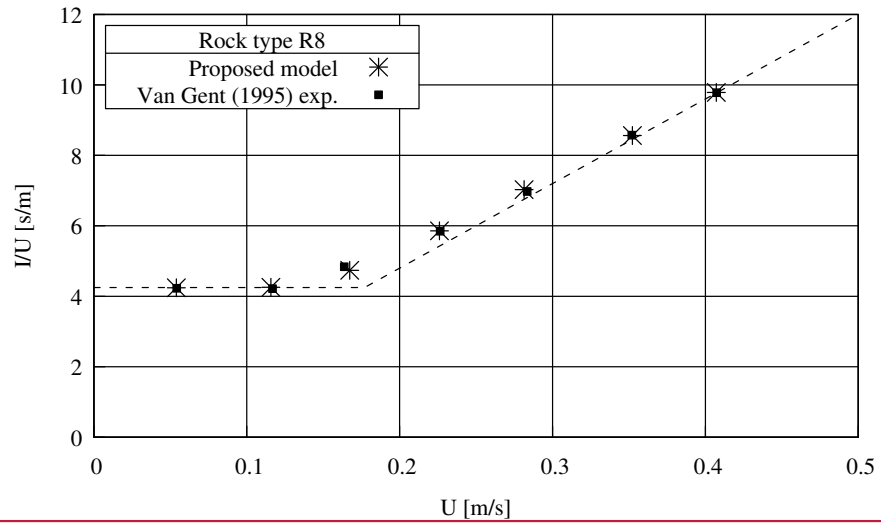
- The model results and recalibration make it clear that an additional term for transitional flow conditions (Lin and Karunarathna, 2007) is obsolete
- These models superpose linear and nonlinear drag components instead of using either linear or nonlinear drag

Calibration of proposed eff. viscosity model









New model parameters

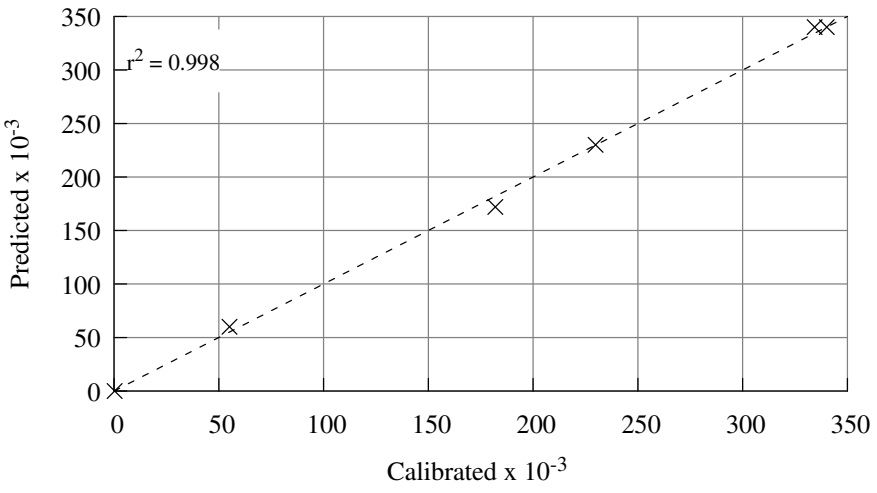
$$\mu^r = \max\left[1, \delta_l, \delta_t Re_P\right]$$

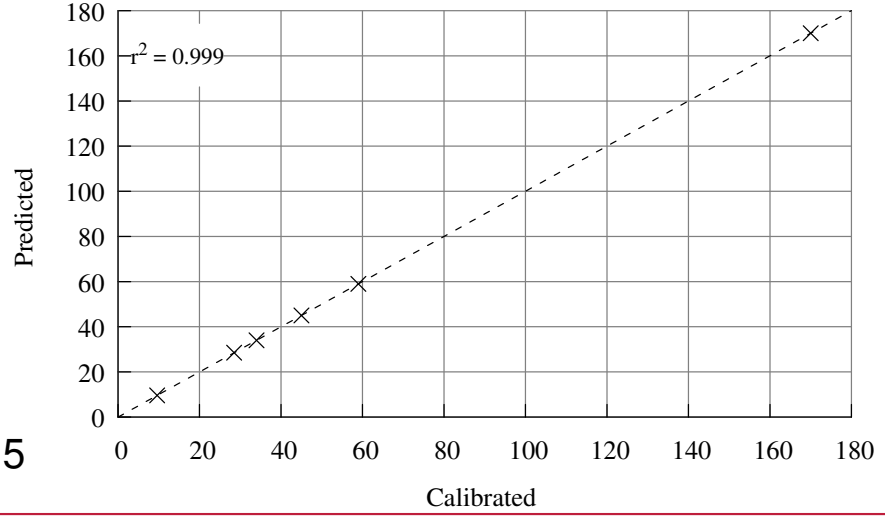
$$Re_P = \frac{D_{50}|\overline{U}|}{\nu}$$

- Linear and nonlinear parameters

$$\delta_l = 720798.65 + 241929.15 \times {}^{D85}/_{D15} \times n + 270422446.46 * \times D_{50}^2 - 53815452.76 \times D_{EQ} \times n$$

$$\delta_t = 503.33 + 9184.52 \times D_{50} - 25.40 \times n - 28.04 \times {}^{l}/_{t} - 191.35 \times {}^{D_{85}}/_{D_{15}} - 14355.29 \times D_{15}$$



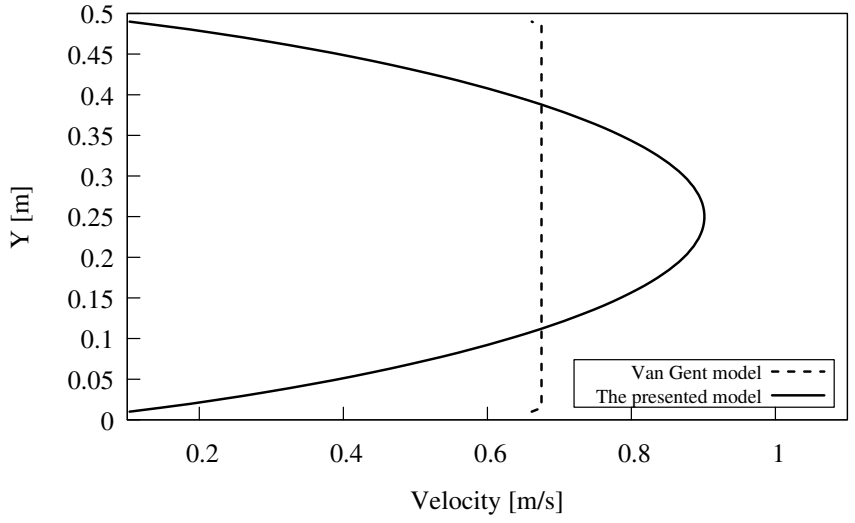


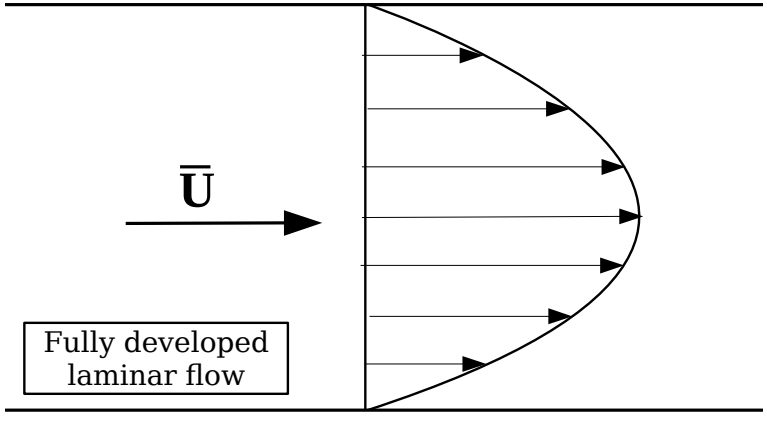
Approximate model link to Darcy permeability

- The proposed eff. viscosity model laminarizes the flow
- Sink term: uniform velocity profile - eff. viscosity: parabolic curve
- The viscous shear stresses can be approximated and equalized to Darcy's drag

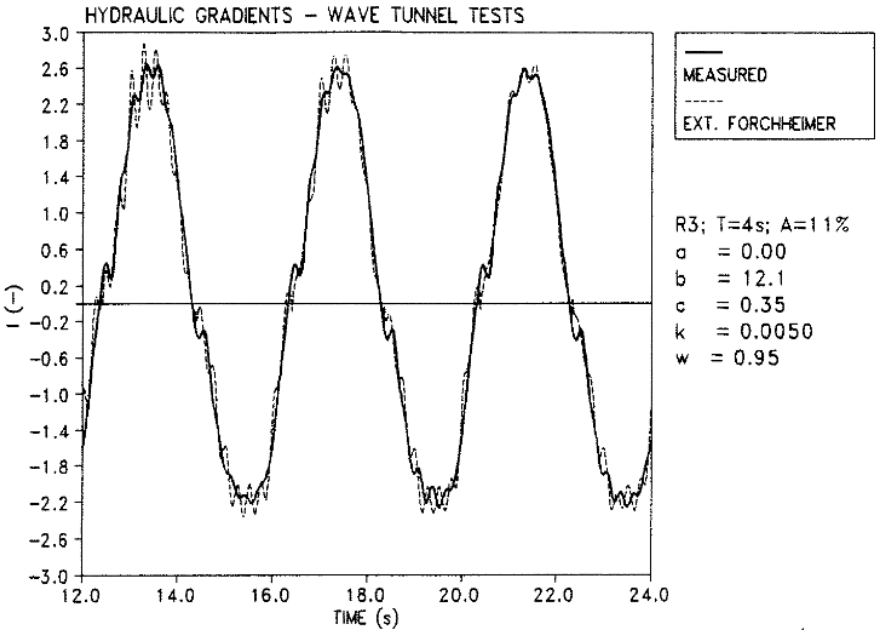
$$\frac{\delta_l}{n}\nabla\cdot\overline{\boldsymbol{\tau}} = \frac{\rho g}{K}\overline{\mathbf{U}}$$

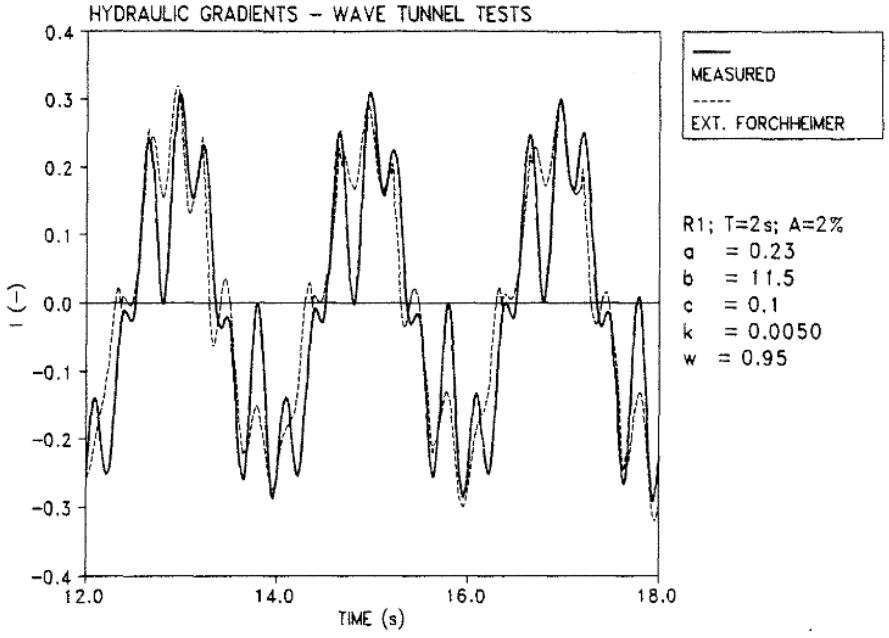
$$\delta_l = \frac{n\rho g}{\psi\mu K}$$





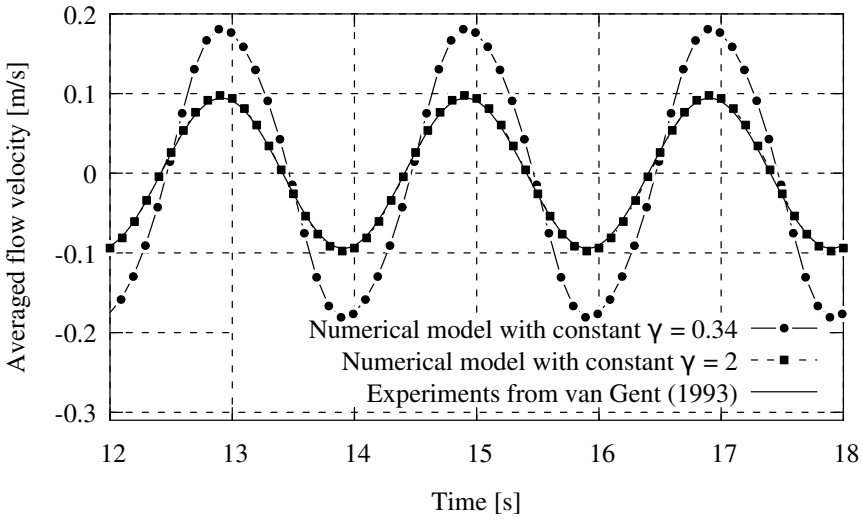
Oscillatory flow: Van Gent (1993) results

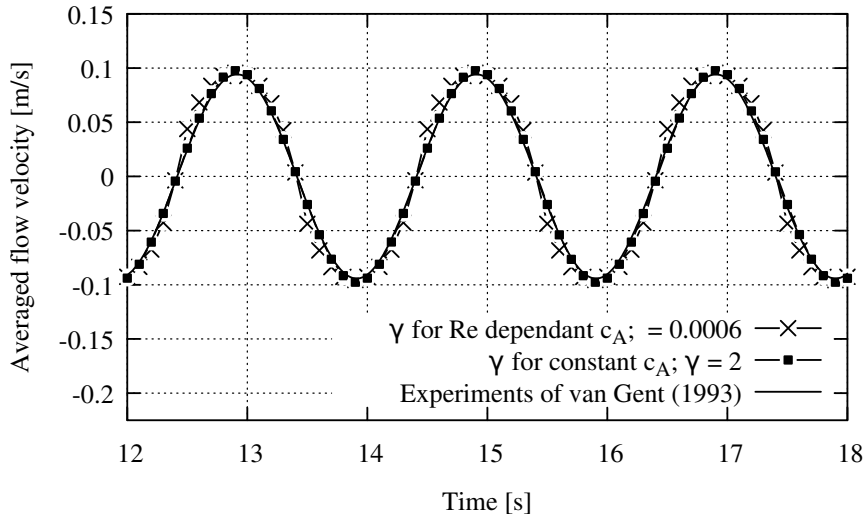




- Results from experiences vary in conforming to a harmonic function
- Experiments with higher periods and higher amplitudes give better results
- Period and pressure amplitude are measured from curves for input to the numerical simulations

Oscillatory flow: Fitted numerical results





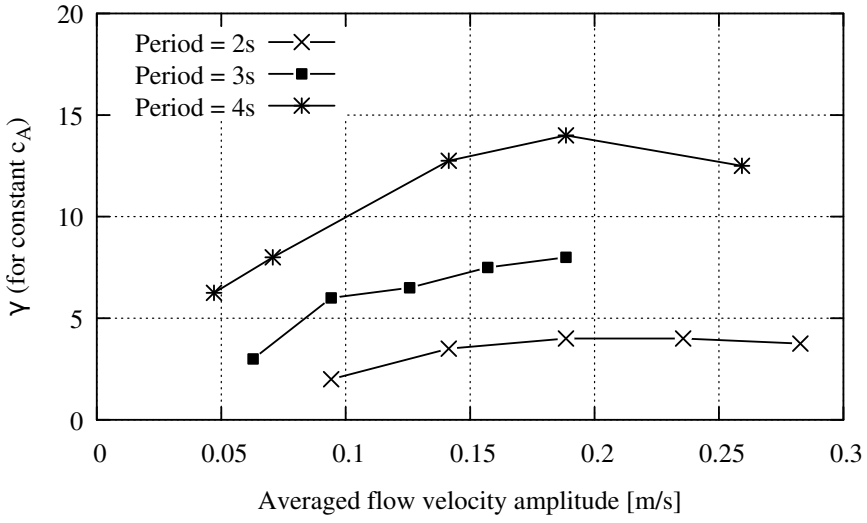
- Fitted two types of c_A: typical form and Re_P dependant form:

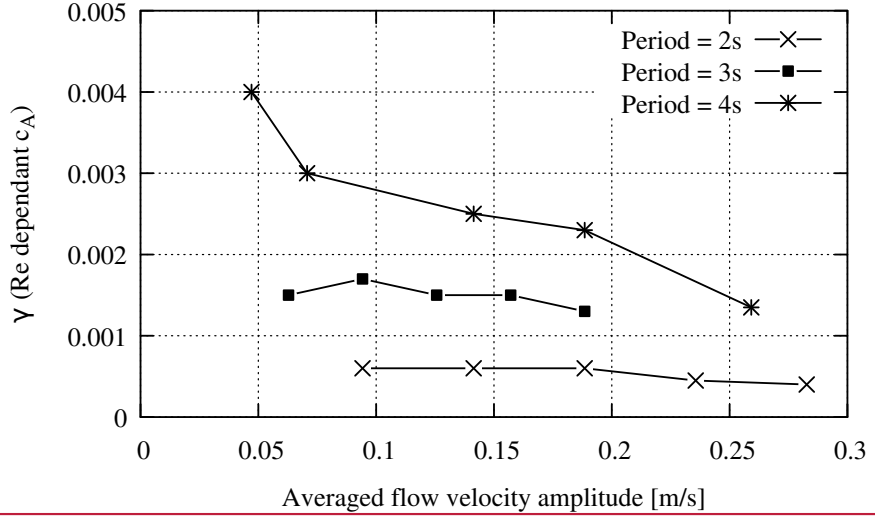
$$c_A = \gamma Re_P \frac{(1-n)}{n}$$

- For constant c_A a value of 0.34 is not universal (see example)
- Fitting results to a Re_P dependant c_A is possible

Oscillatory flow: γ value

- For the van Gent tests, fitting the value of γ
- The range of available results is not sufficient
- γ is *definitely* not 0.34
- Adding Re_P is better, maybe more variables are needed
- More experiments are really needed





Outline

- Introduction
- The *geotechFoam* solver
- Modelling flow through porous media
- **Concluding remarks and outlook**

Concluding remarks and outlook

- Hydro-geotechnical modelling with OpenFOAM: the *geotechFoam* solver
- Download from repository on BitBucket, visit `www.geotechfoam.com`
- Tutorials + "draft" documentation
- Use of numerical modelling as a virtual lab to work in tandem with physical modelling
- Uplift pressure on structures –> flow through porous media –> cyclic/transient flow???
- OpenFOAM® is a registered trademark of OpenCFD Ltd.

Thank you for your attention!

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