Physical and numerical modelling of sand liquefaction

in waves interacting with a vertical wall

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Objectives

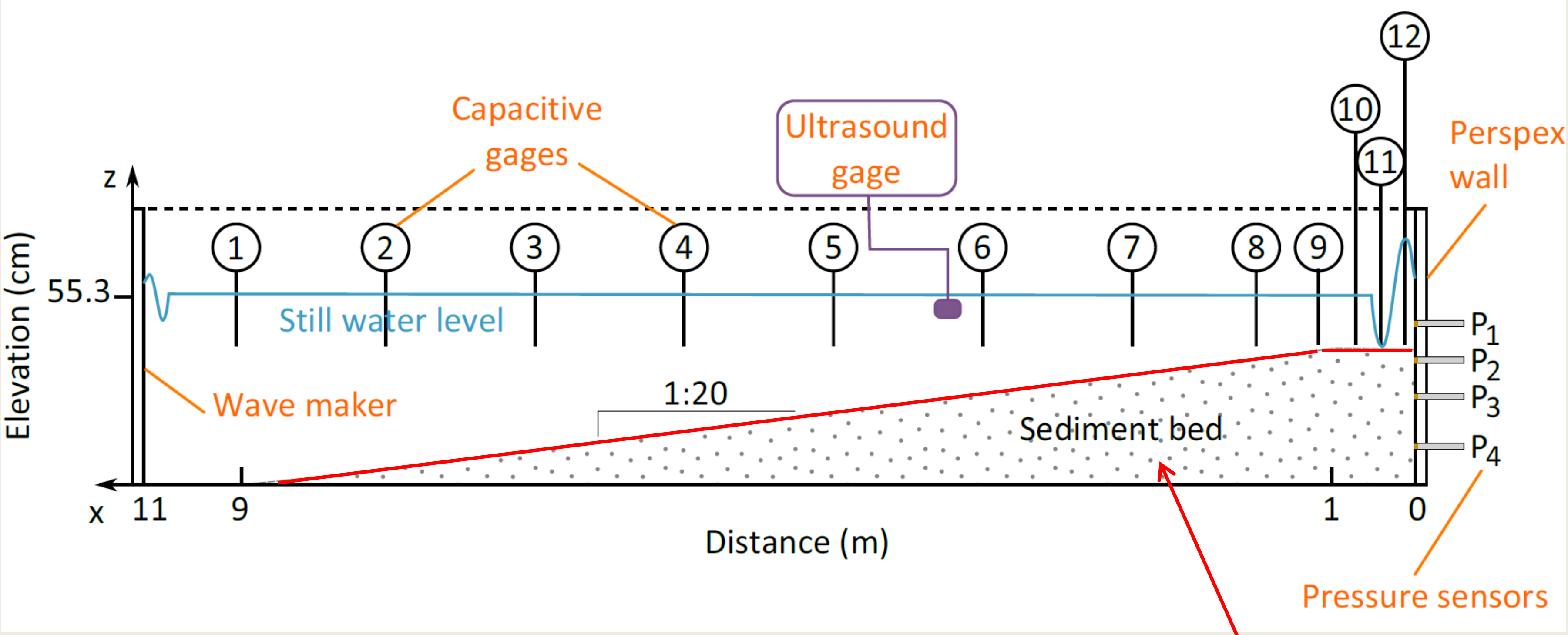
- To evaluate the potential of sandy beds to liquefy near coastal structures

  by momentary liquefaction (Mory et al., 2007)

  liquefaction induced by pore pressure build-up (Sumer et al., 1999)
- To study the links between liquefaction, erosion, scour (de Groot et al., 2006)
- Sensitivity to geo-mechanical parameters and soil gas content

→ Laboratory experiments / numerical model

Physical model



Measurements:

- Pore pressure against the wall
- Free surface displacements
- Bottom profiles (estimation of bed porosity)
- Video observations (erosion depth, soil mobility)

lightweight sediment

d_{50} = 0.64 mm ρ = 1.18

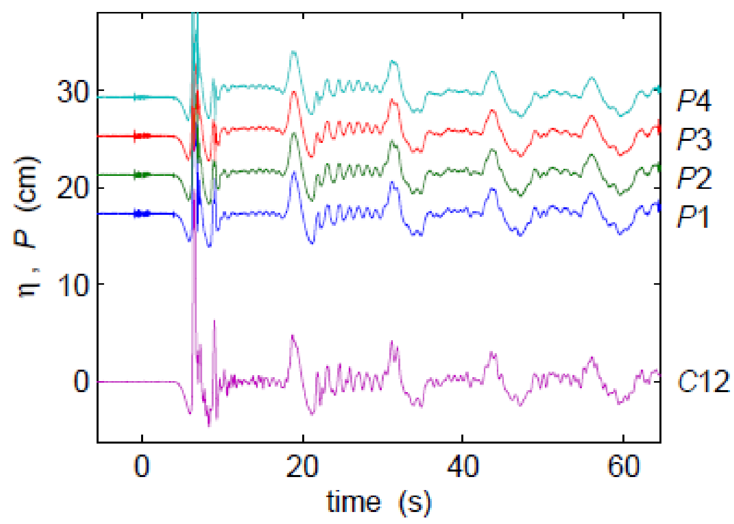
(Grasso et al., 2009)

un-saturated bed

$C_{gas} \sim 1\%$ to 8%

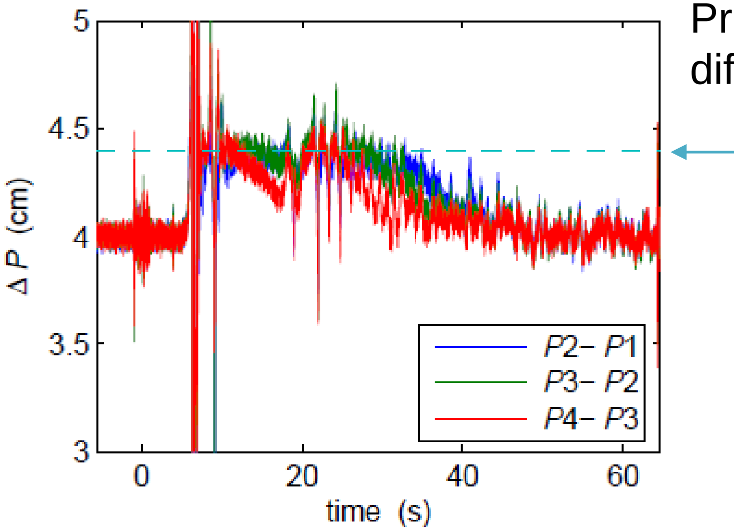
Wave impact induced momentary liquefaction

Loose and unsaturated bed



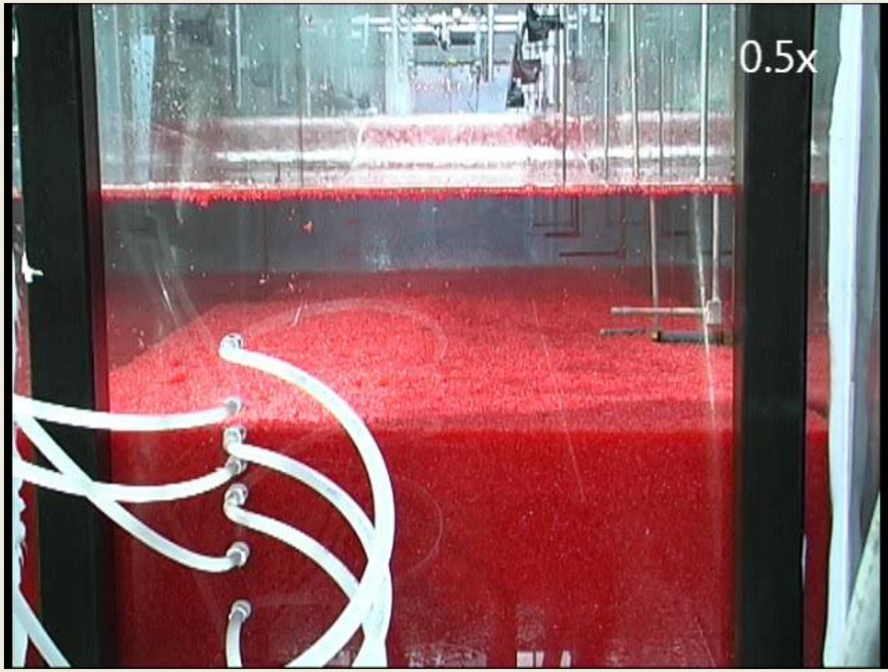
Pore pressure measured against the wall

free surface elevation



Pressure differences

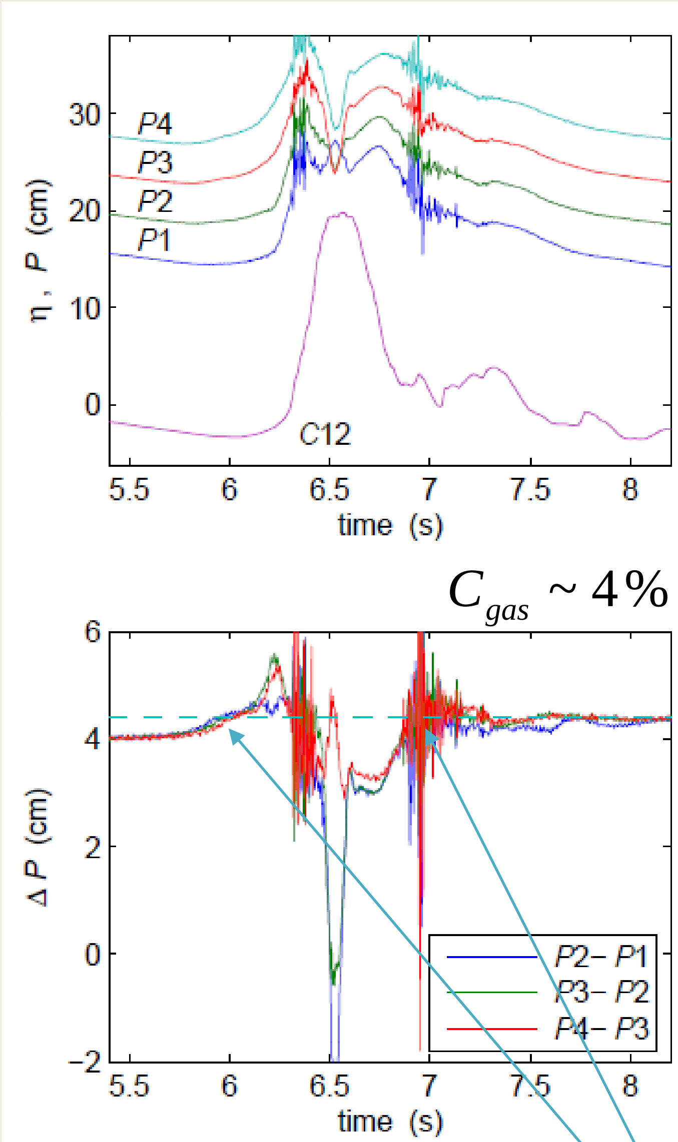
Liquefaction threshold value



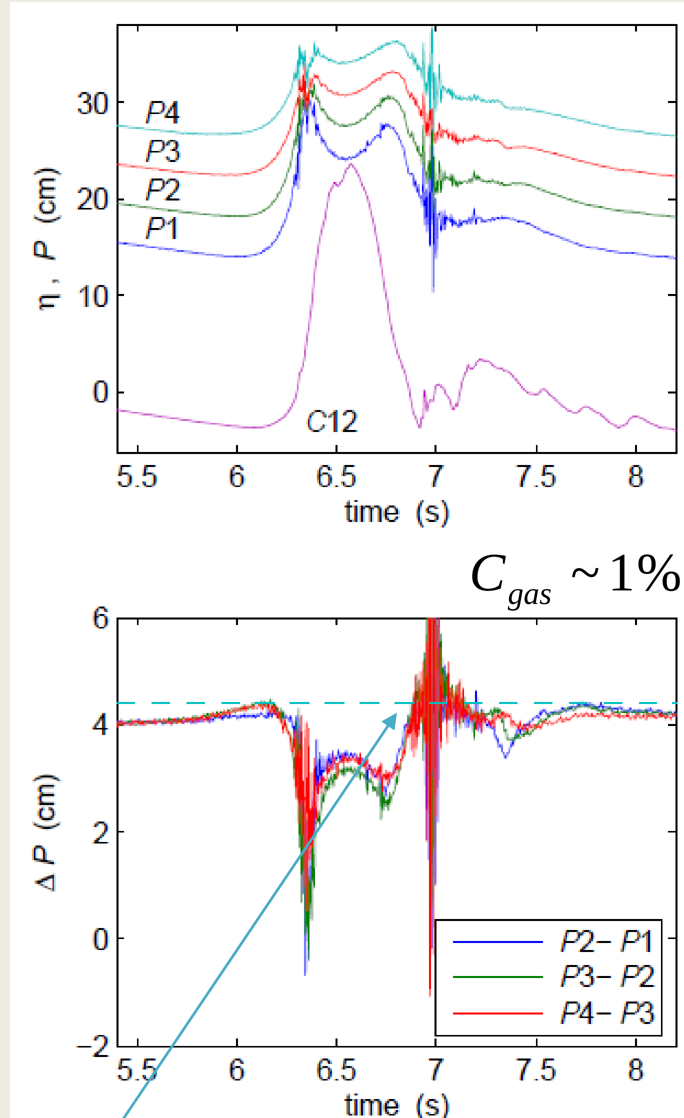
- bed liquefies at wave impact

- characteristic time of liquefied bed to settle ~ 10 s

Loose and unsaturated bed



Compact and “saturated” bed



Liquefaction

Cyclic loading   *T* = 1.55 s   *a* = 1 cm   **loose, unsaturated bed**

Liquefaction
after
~ 20 cycles

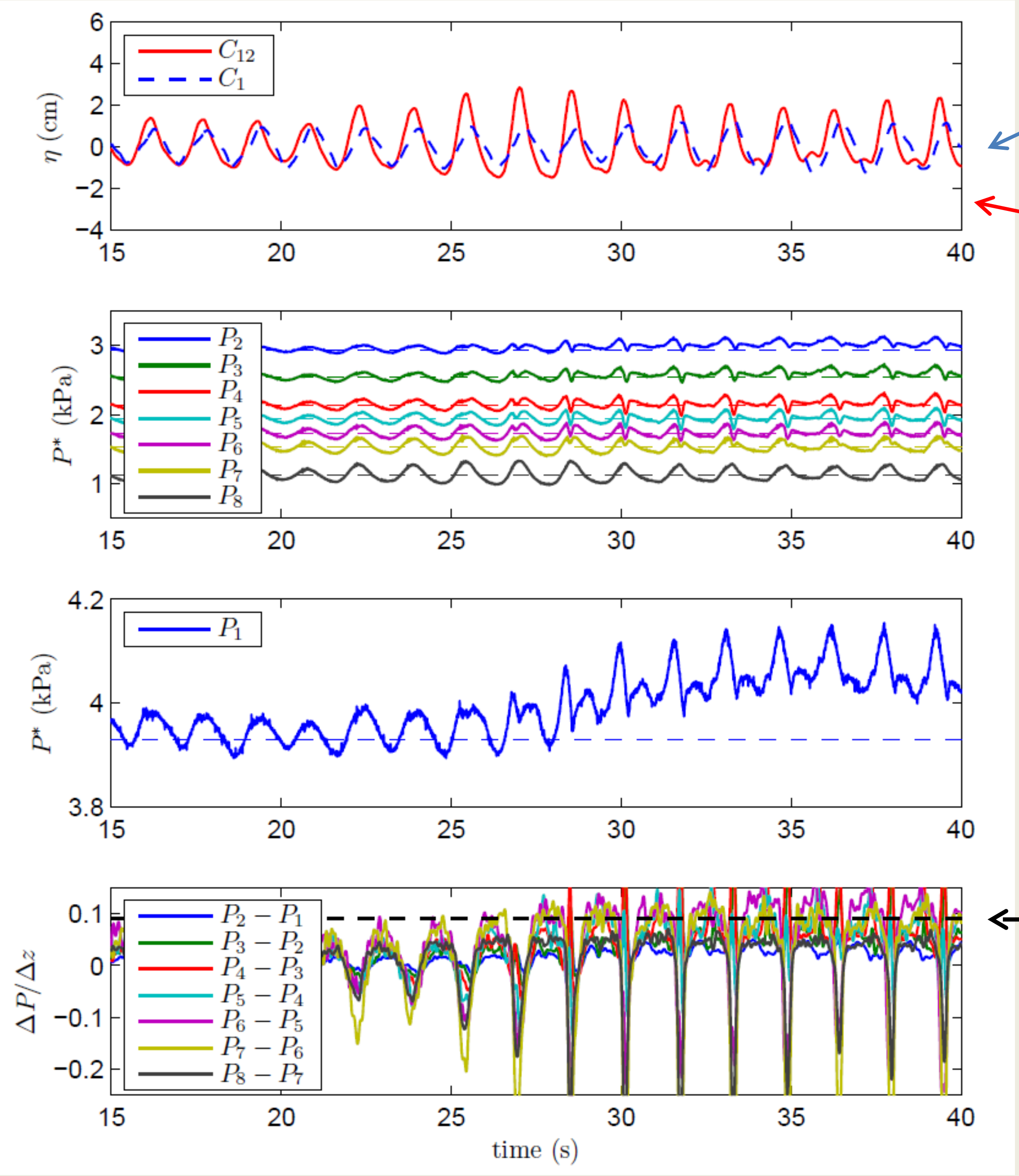
End of
compaction
after
~ 80 cycles

Cyclic loading T = 1.55 s a = 5 mm **loose, unsaturated bed**

Surface elevation

Pressure

Pressure gradient



at the wave-maker

at the wall

lowest sensor

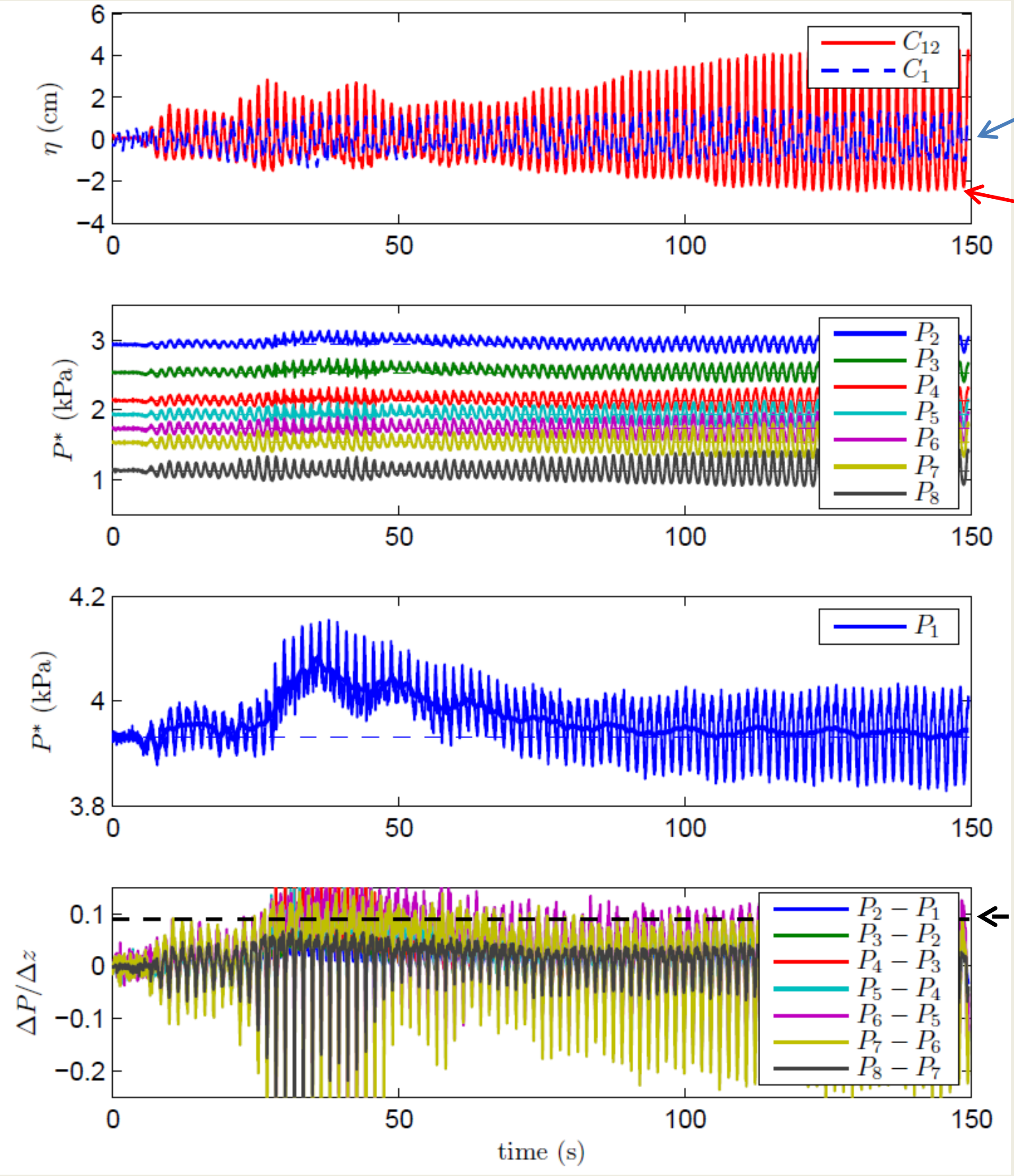
liquefaction threshold

Cyclic loading T = 1.55 s a = 5 mm **loose, unsaturated bed**

Surface elevation

Pressure

Pressure gradient



at the wave-maker

at the wall

lowest sensor

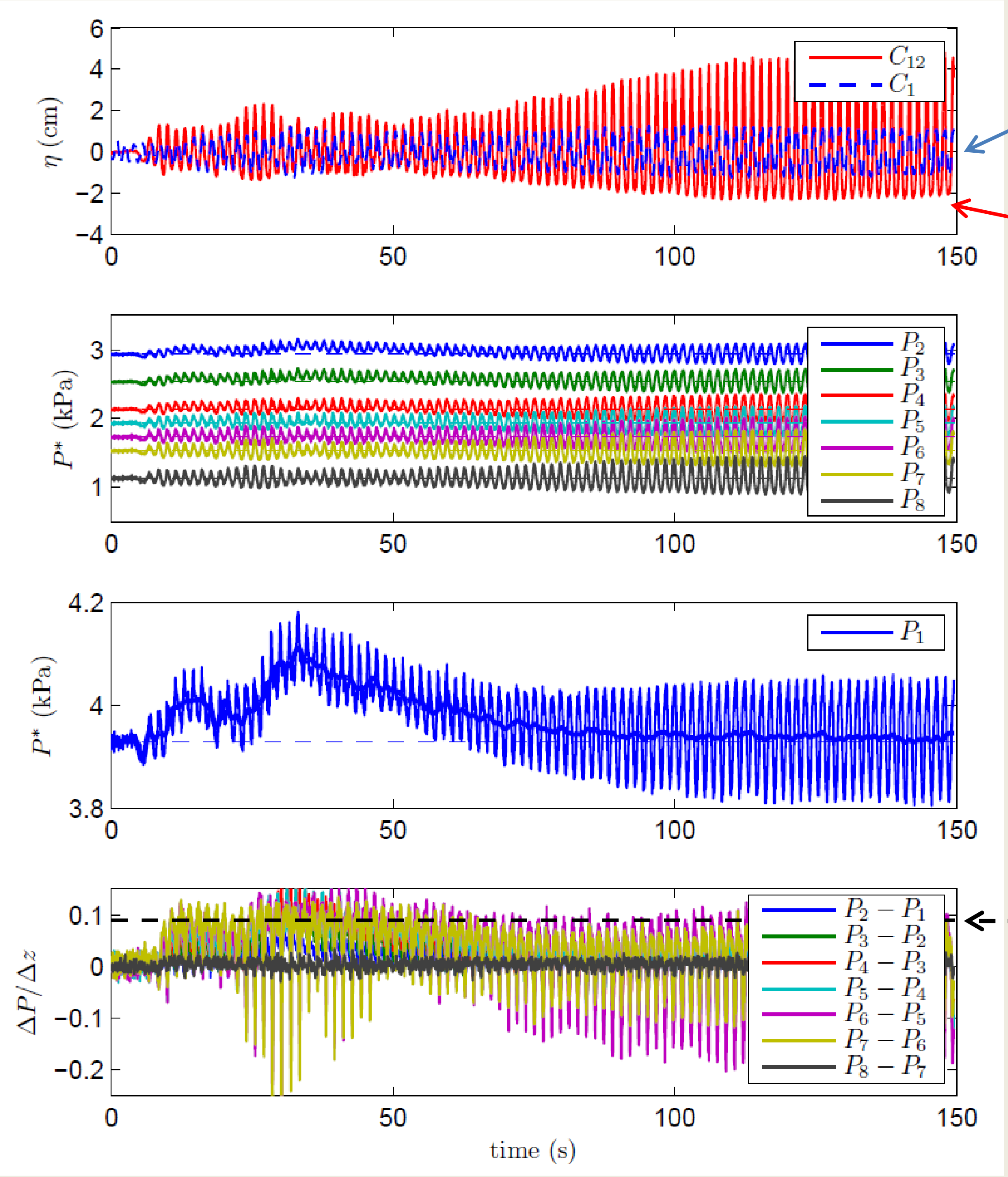
liquefaction threshold

Cyclic loading T = 1.55 s a = 5 mm **loose, “saturated” bed**

Surface elevation

Pressure

Pressure gradient



at the wave-maker

at the wall

lowest sensor

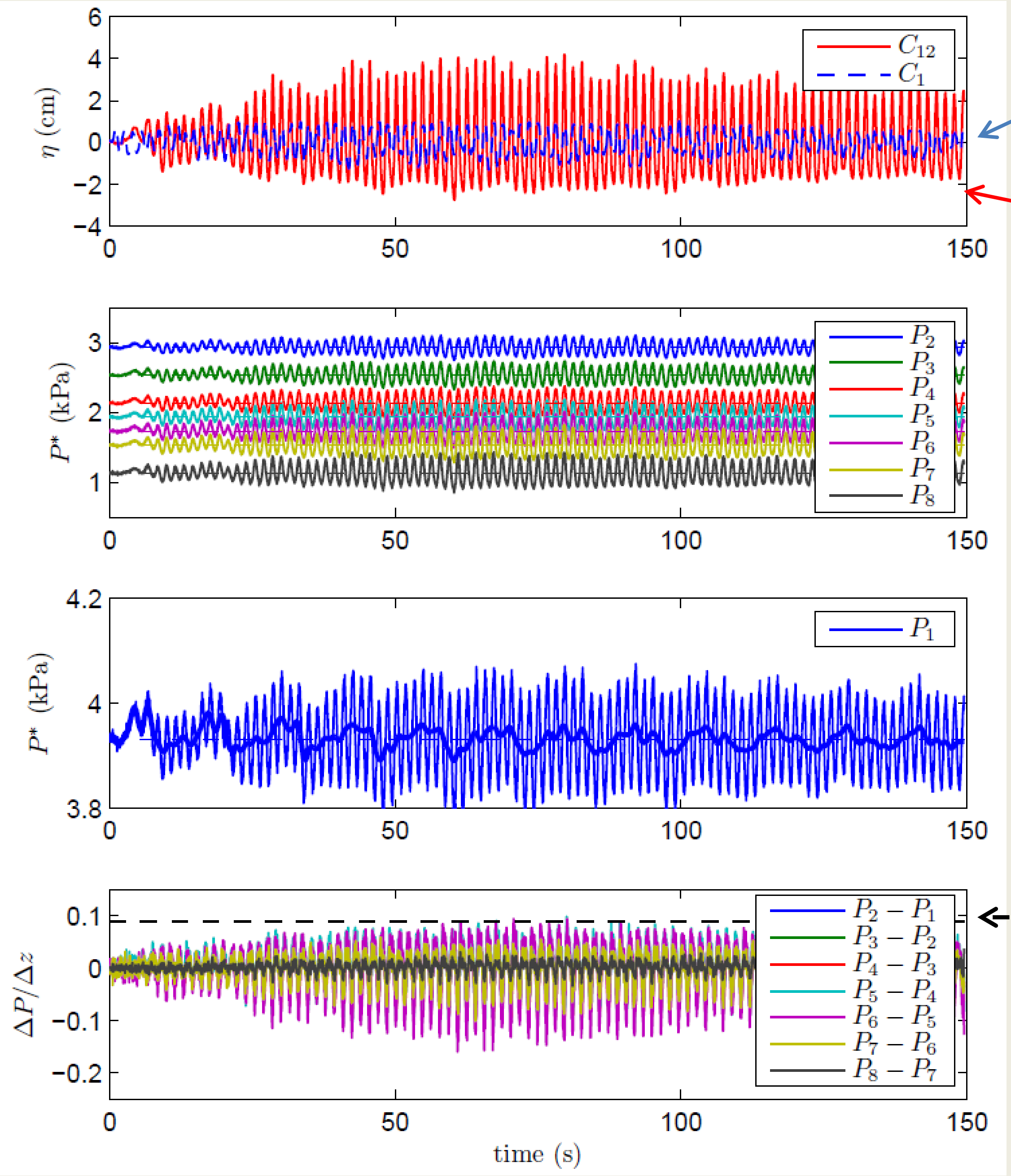
liquefaction threshold

Cyclic loading $T = 1.55$ s $a = 5$ mm **compact, “saturated” bed**

Surface elevation

Pressure

Pressure gradient



at the wave-maker

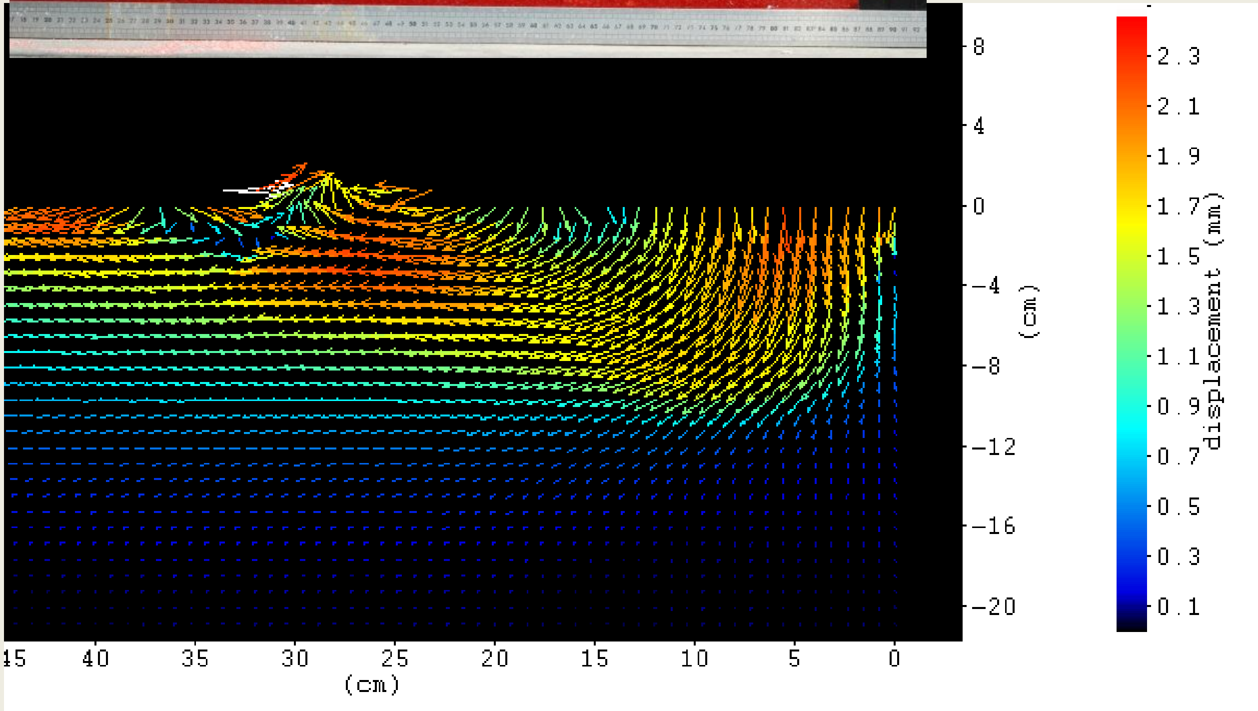
at the wall

lowest sensor

liquefaction threshold

PIV analysis

Displacements fields



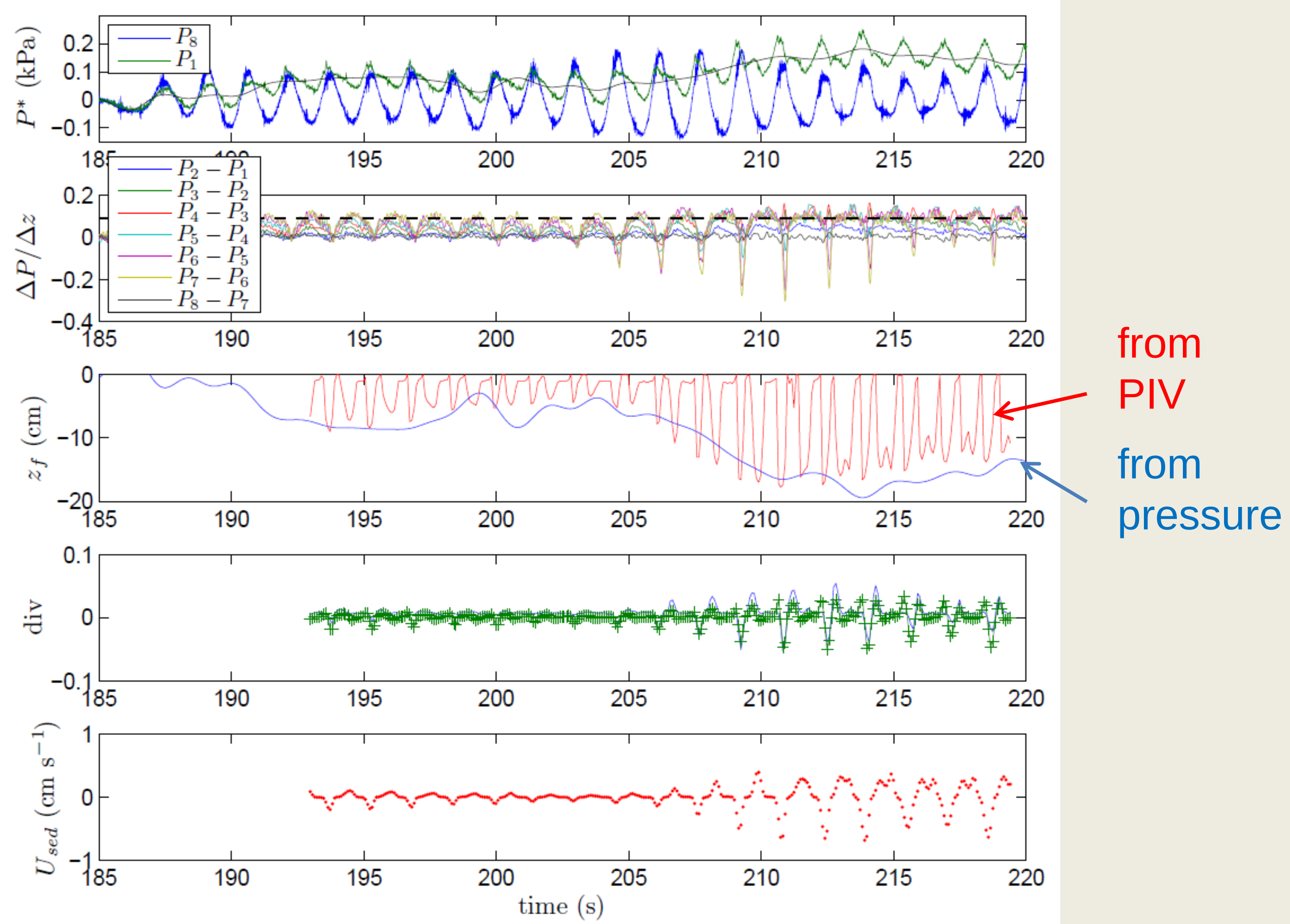
Pressure

Pressure gradient

Liquefaction depth

compaction

mean velocity

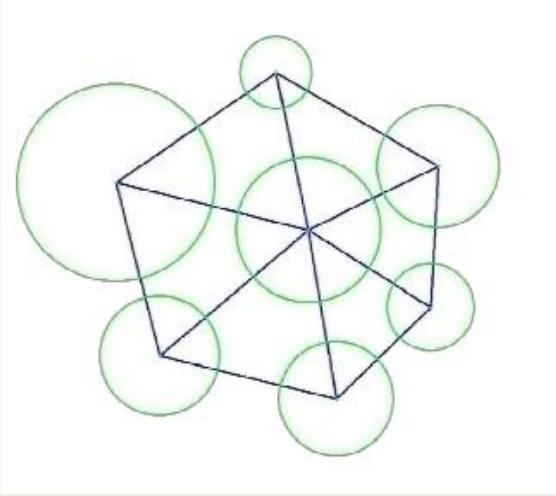


THE PORE-SCALE FINITE VOLUMES MODEL

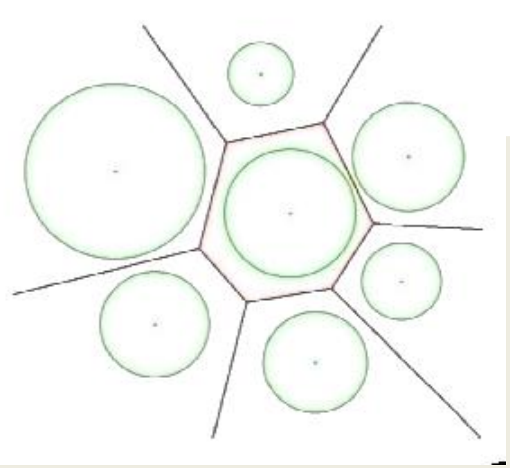
- **Coupled** numerical model for the simulations of **fluid-particle systems**
- The **discrete element method** (DEM) is used for the modelling of the solid phase
- The DEM is combined with a **flow model** for **incompressible** pore fluids

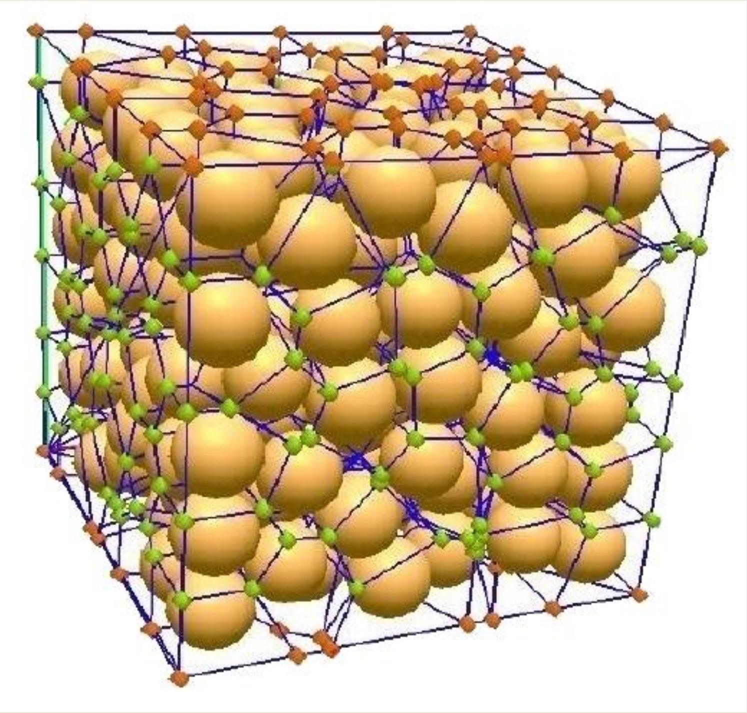
FINITE VOLUMES DISCRETIZATION

REGULAR TRIANGULATION
one pore =
one tethraedron
in 3-dimensions
(one value of pressure per pore)



VORONOI TESSELATION:
dual to the triangulation, it represents a "pore map" that allows the formulation of the problem



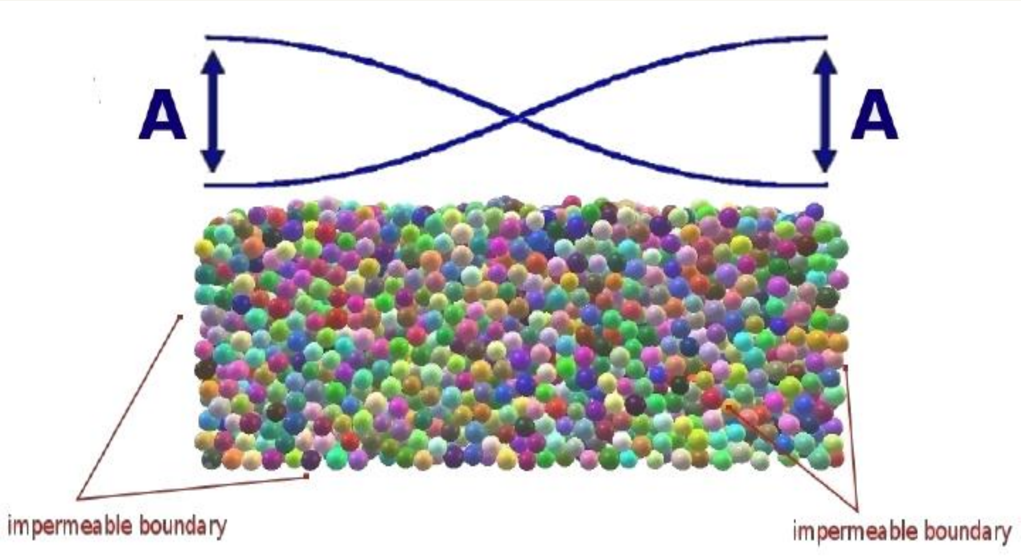


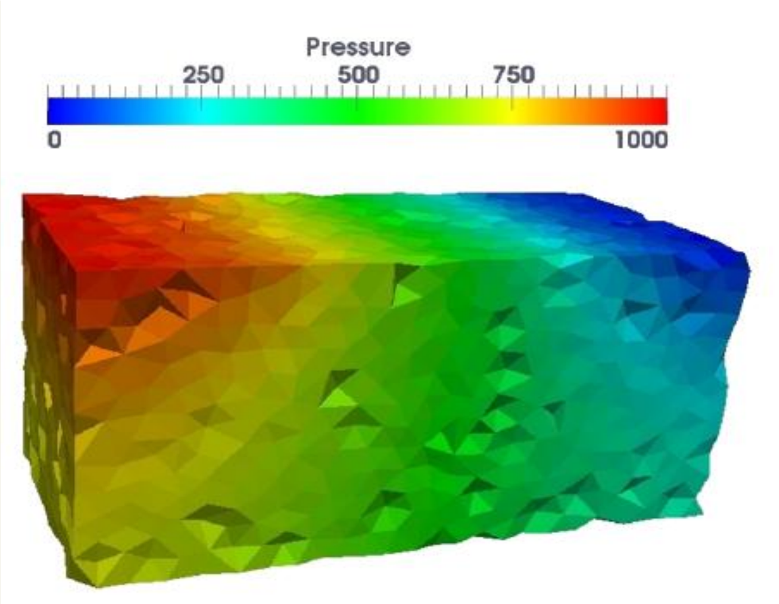
The PFV model

E. Catalano, PhD thesis, 2012

THE PORE-SCALE FINITE VOLUMES MODEL

Wave action simulated by imposing a sinusoidal pressure profile at the seabed surface

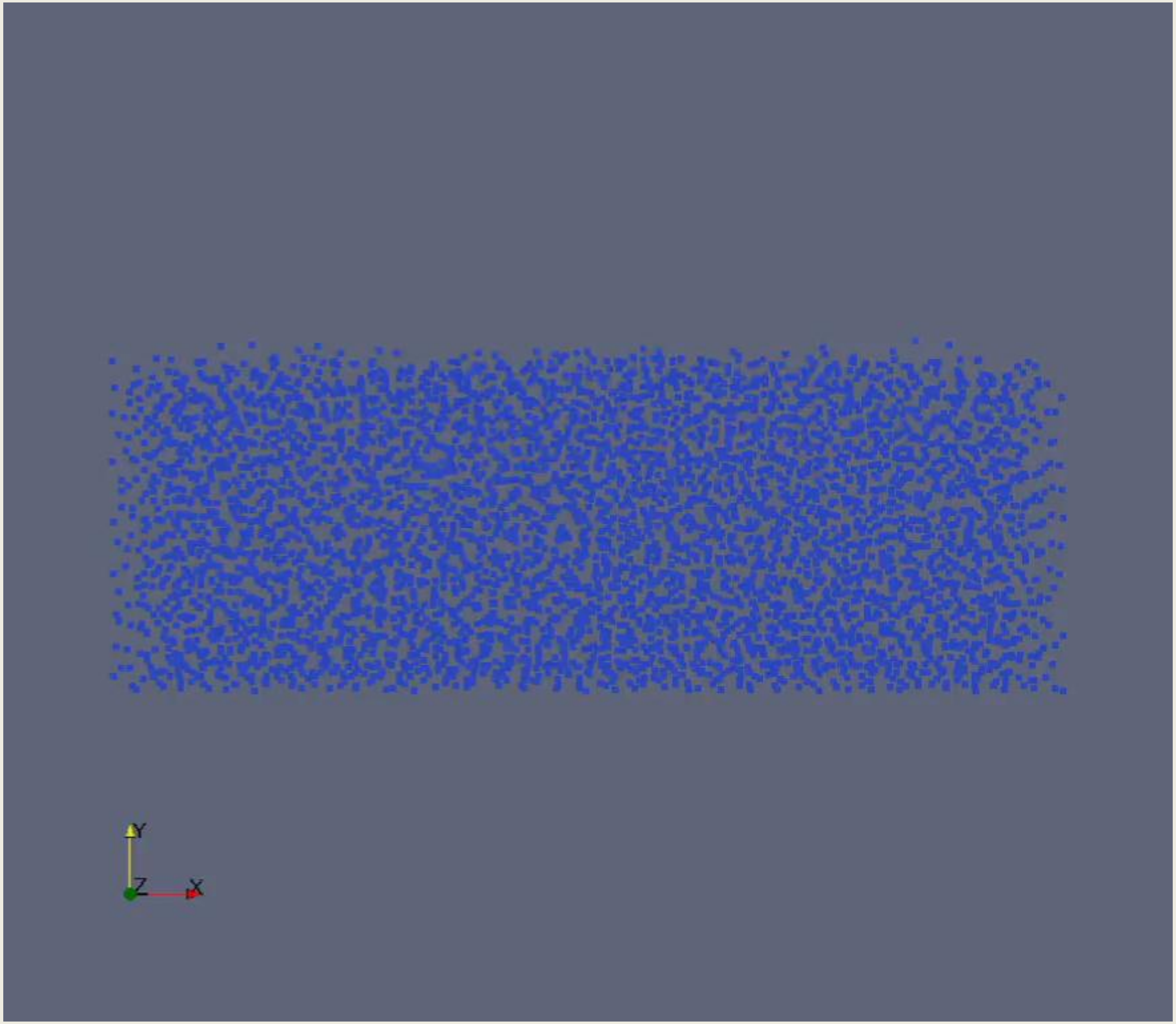




- 5000 particles
- d_{50} = 6.1 cm ρ = 2.6
- large viscosity μ = 100 Pa s

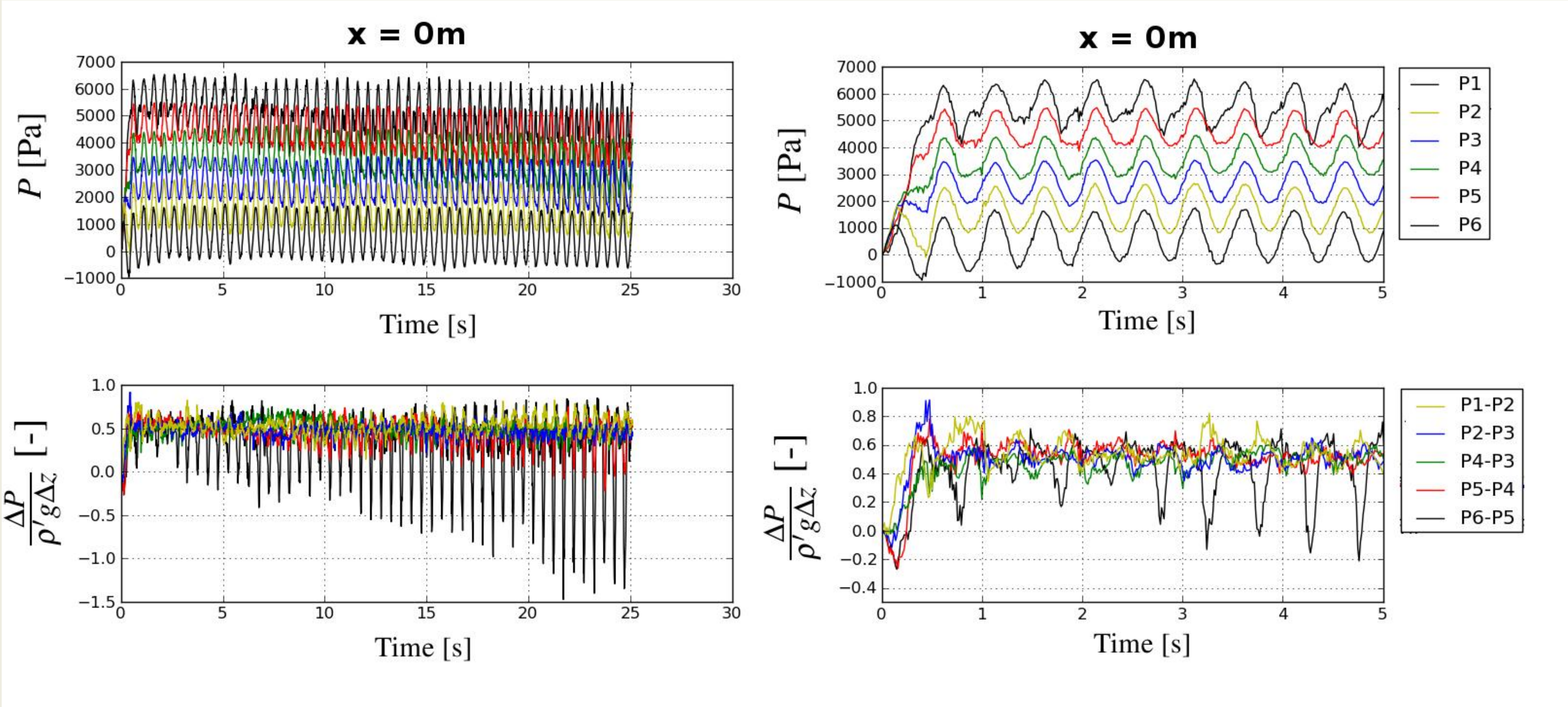
  to get a characteristic time of consolidation ~ 10 s

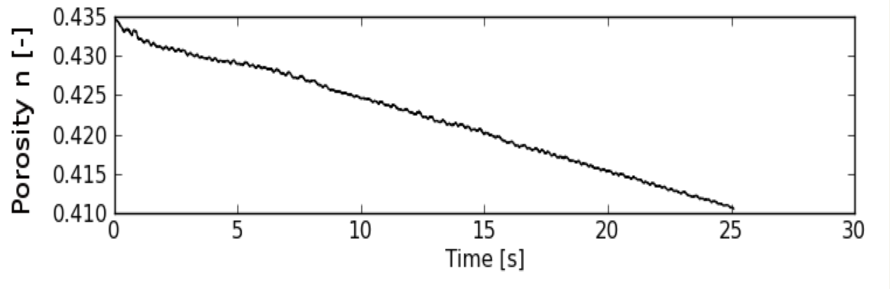
DEM-PFV



Pressure at the wall, every12cm in the vertical loose, saturated bed

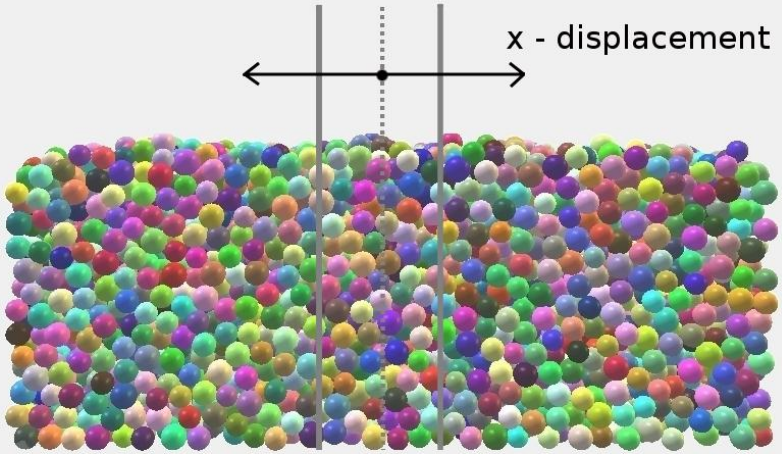
DEM-PFV

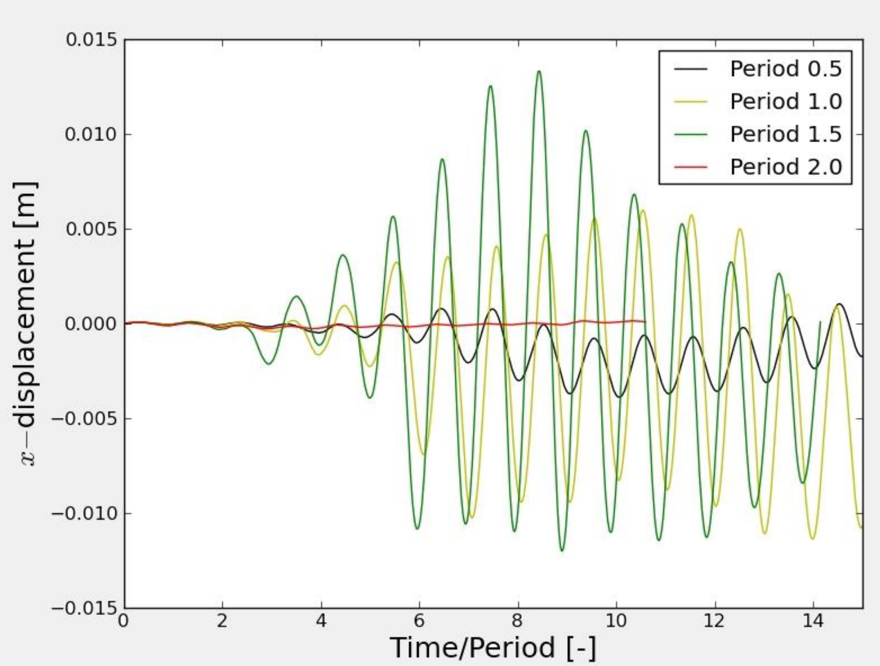


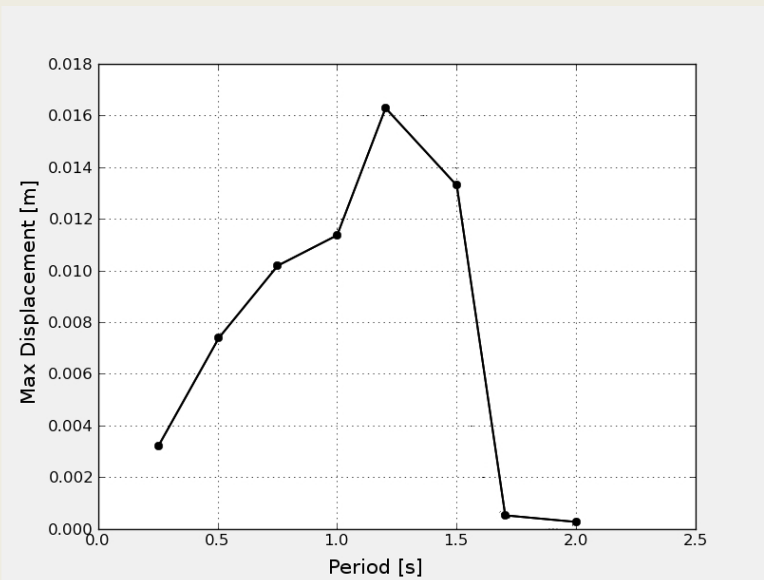


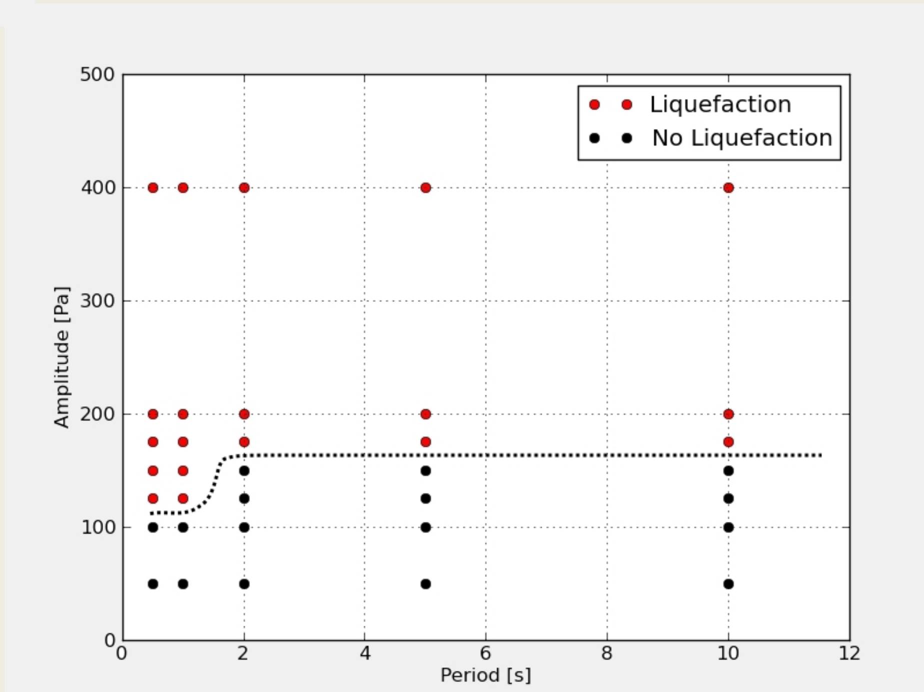
Overall good qualitative agreement with experiments !

Liquefaction depends on drainage time / wave period









Conclusions

- Liquefaction reproduced in the laboratory using lightweight coarse sediment
  - Pore pressure build-up induced by cyclic loading
  - Wave-induced momentary liquefaction
- Major role of soil gas content
  - reduces build-up / enhances momentary liquefaction
- Liquefaction by pore-pressure build-up reproduced with DEM-PFV
- Better description of dilatation / compaction phases
- Overall bed compaction along repeated cycles / runs
- Large zones of liquefied soil ‘available’ for transport

Perspectives

- Better quantification of the soil parameters (G, ν, n, …) and the gas content in the experiments
- Use of Sakai et al. (1992) model to relate soil parameters to pressure damping
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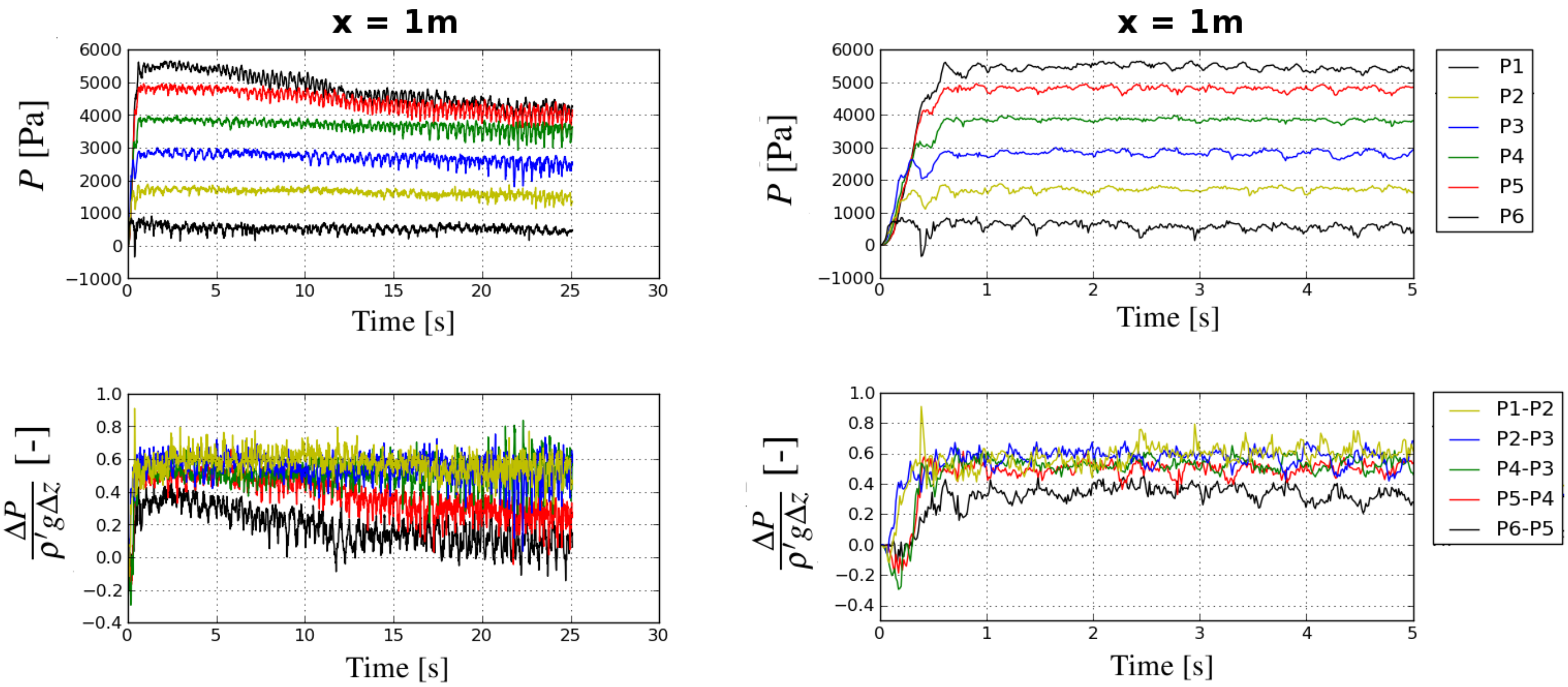
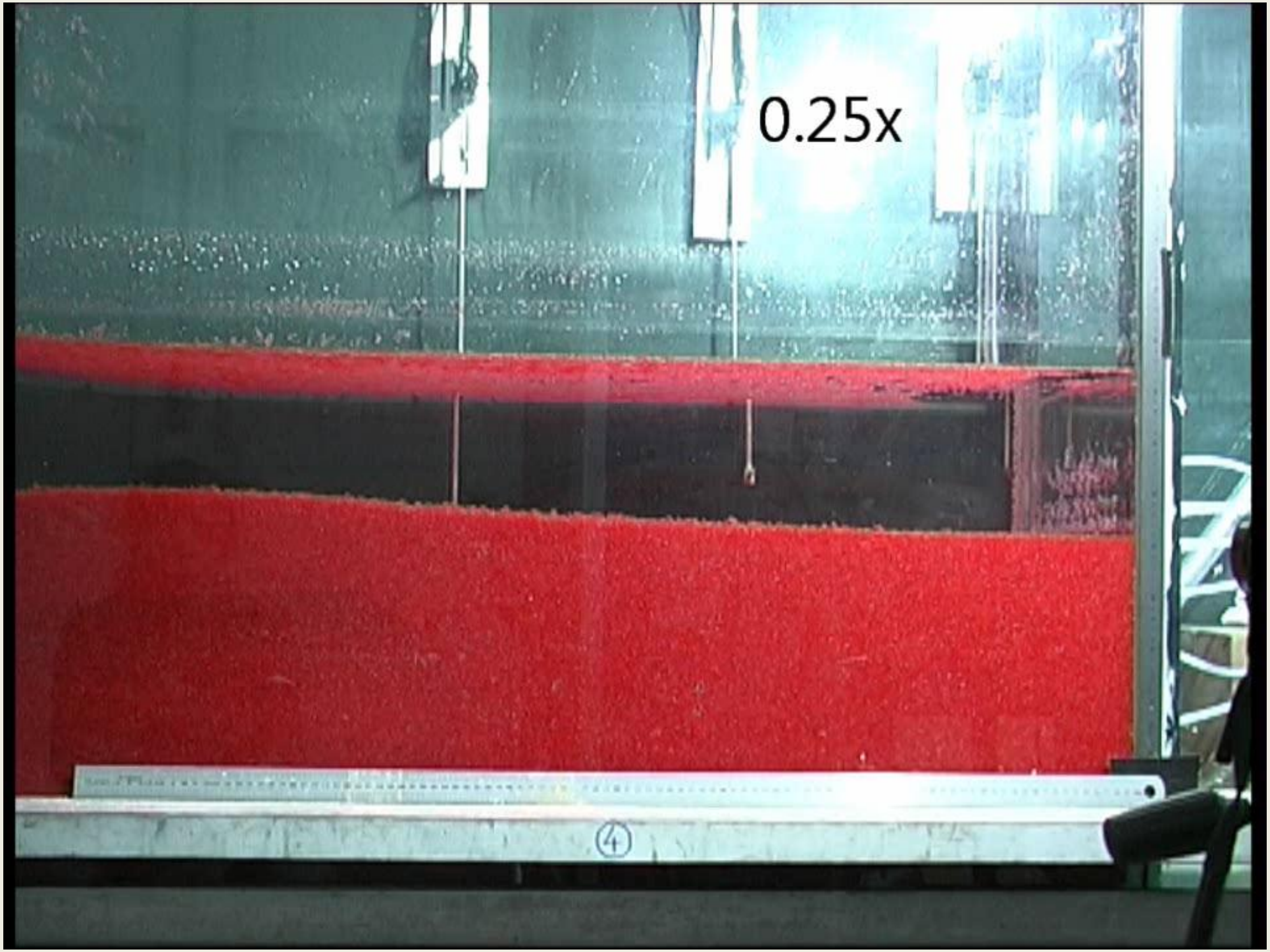
Thank you for your attention !

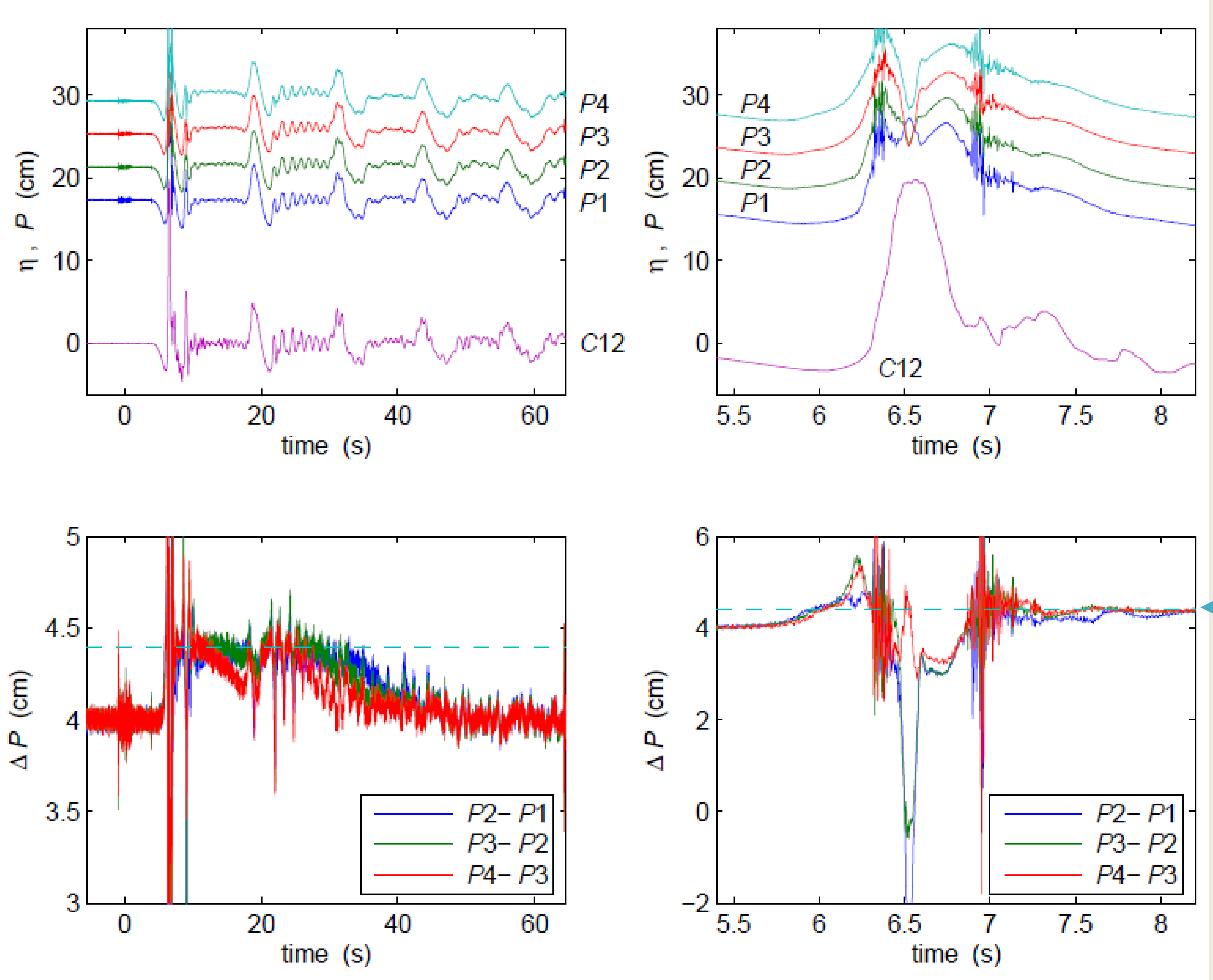

x = 1m
P [Pa]
Time [s]
x = 1m
P1
P2
P3
P4
P5
P6
ΔP/ρ'gΔz [-]
P1-P2
P2-P3
P4-P3
P5-P4
P6-P5

Wave breaking, side view



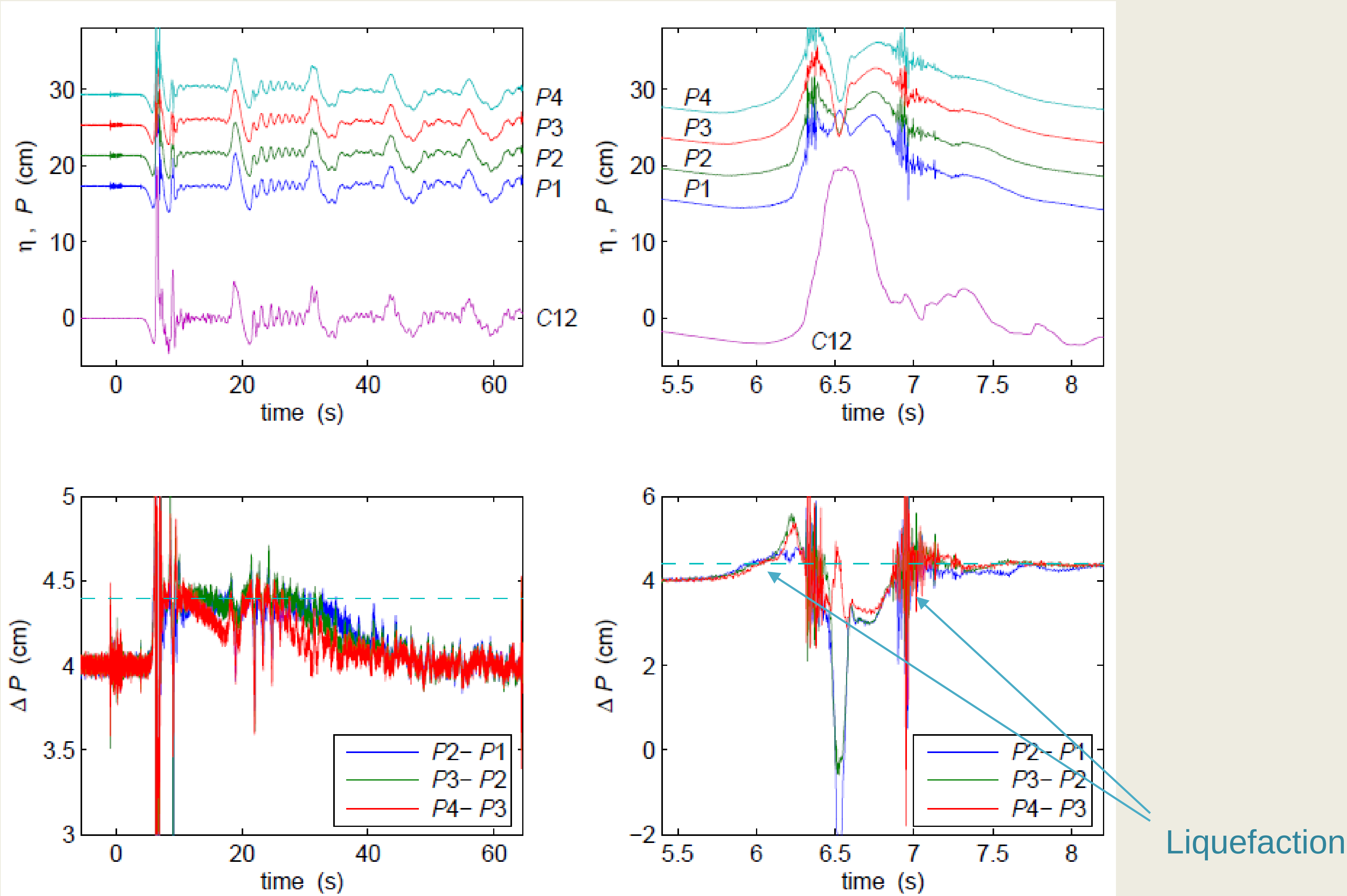
Loose and unsaturated bed, rear view

Loose and unsaturated bed

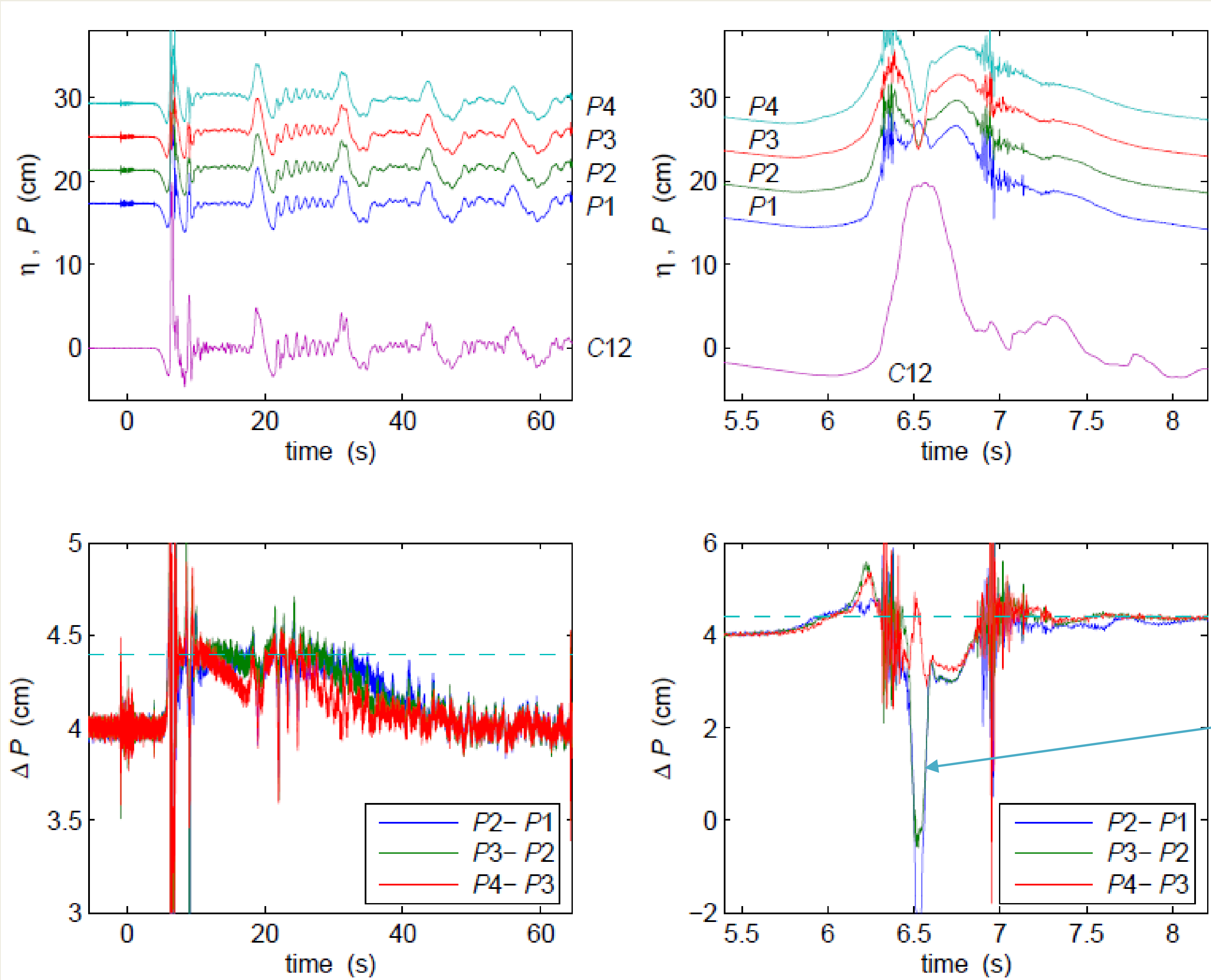


Liquefaction threshold value

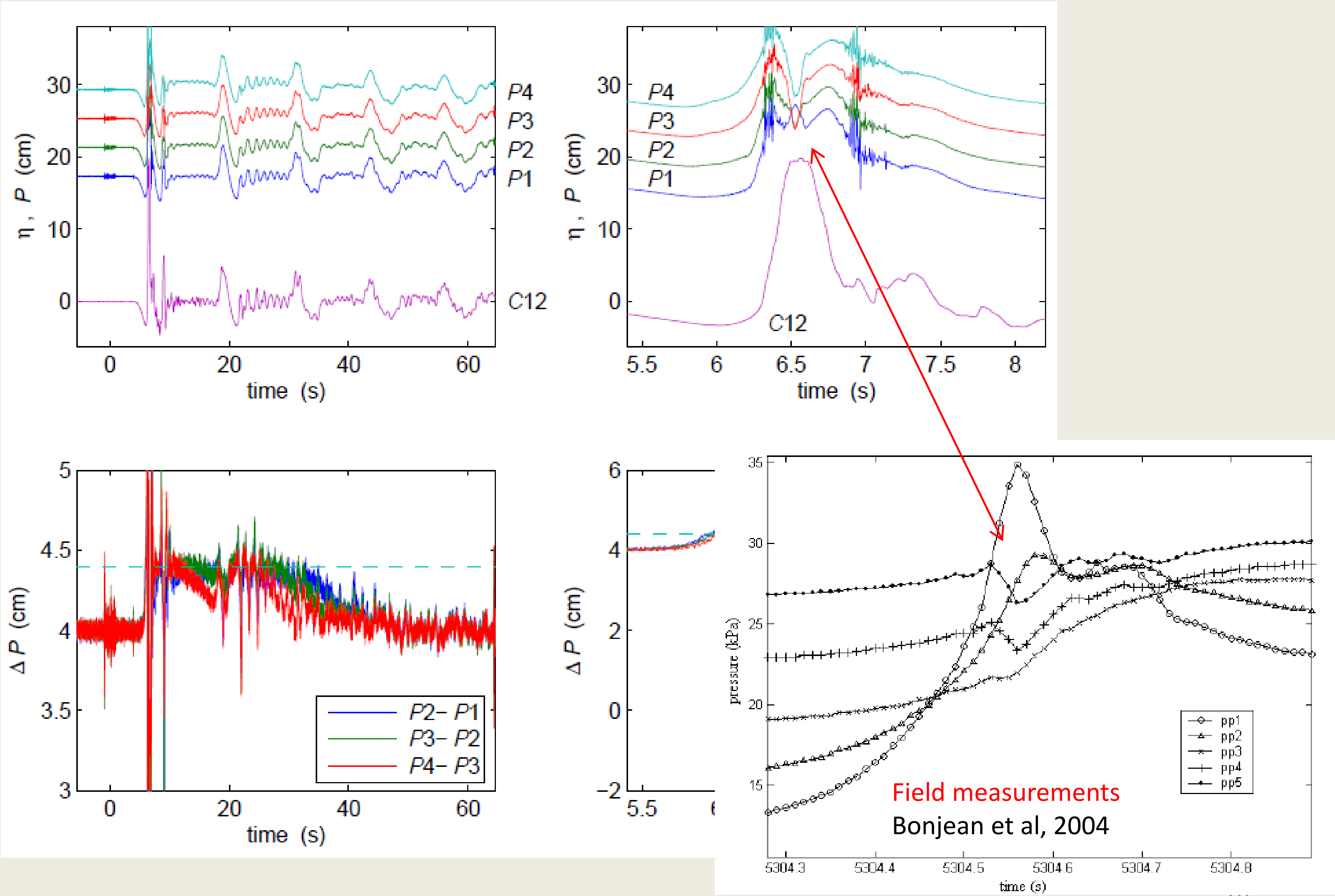
Loose and unsaturated bed



Loose and unsaturated bed

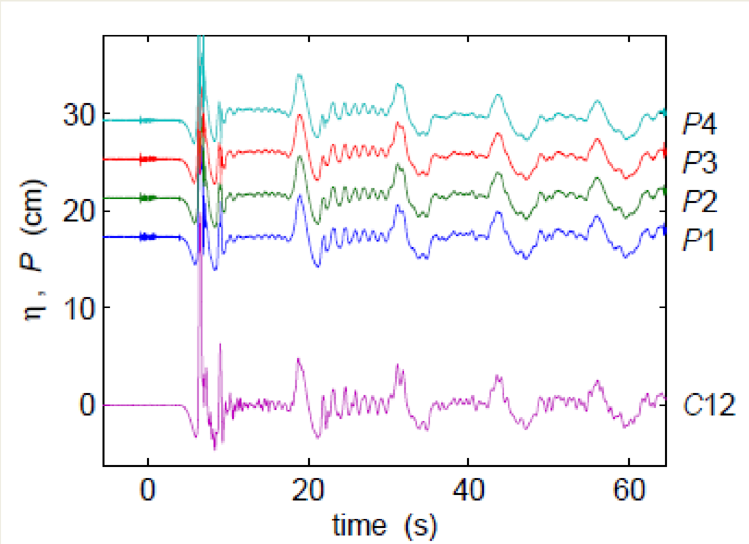


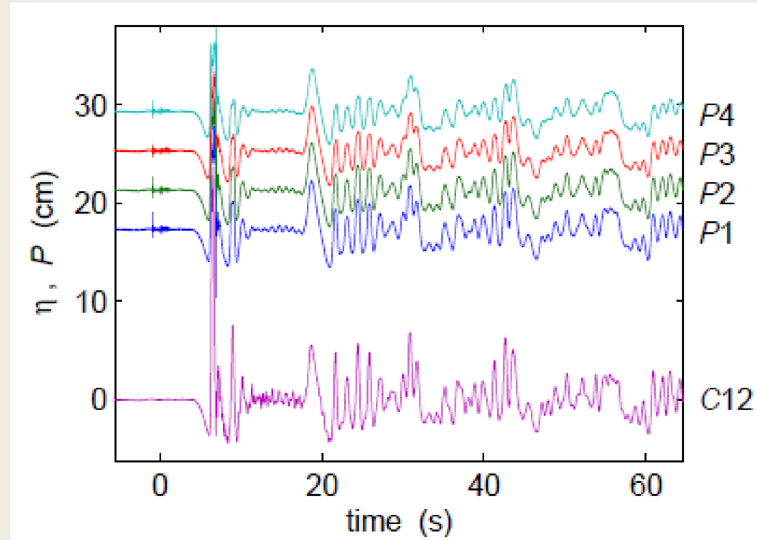
Loose and unsaturated bed



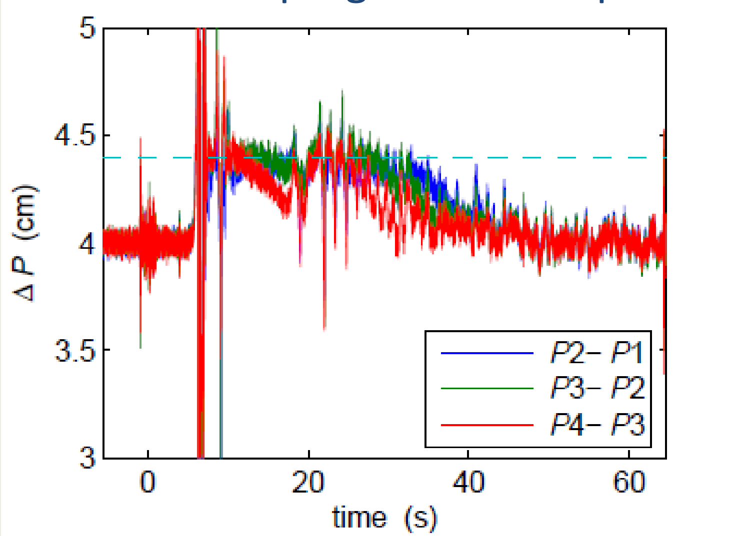
Loose and unsaturated bed

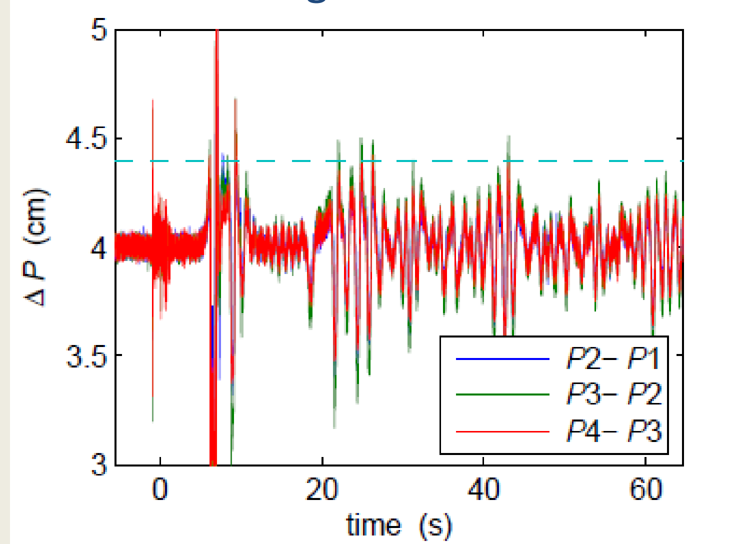
After 6 runs





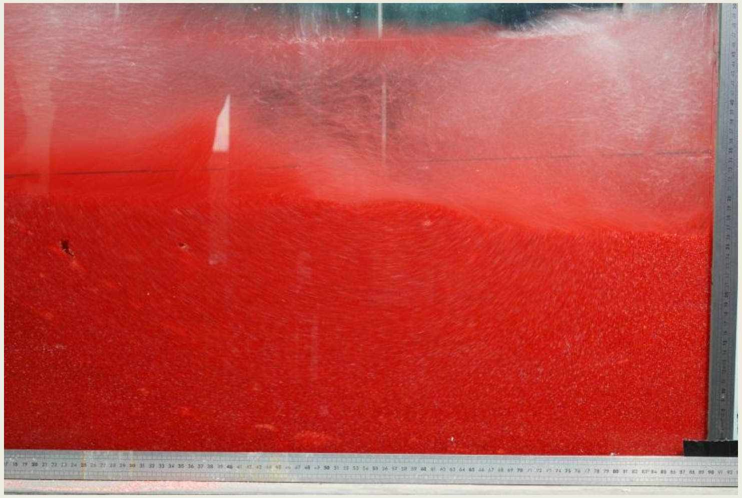
progressive compaction & saturation along the runs

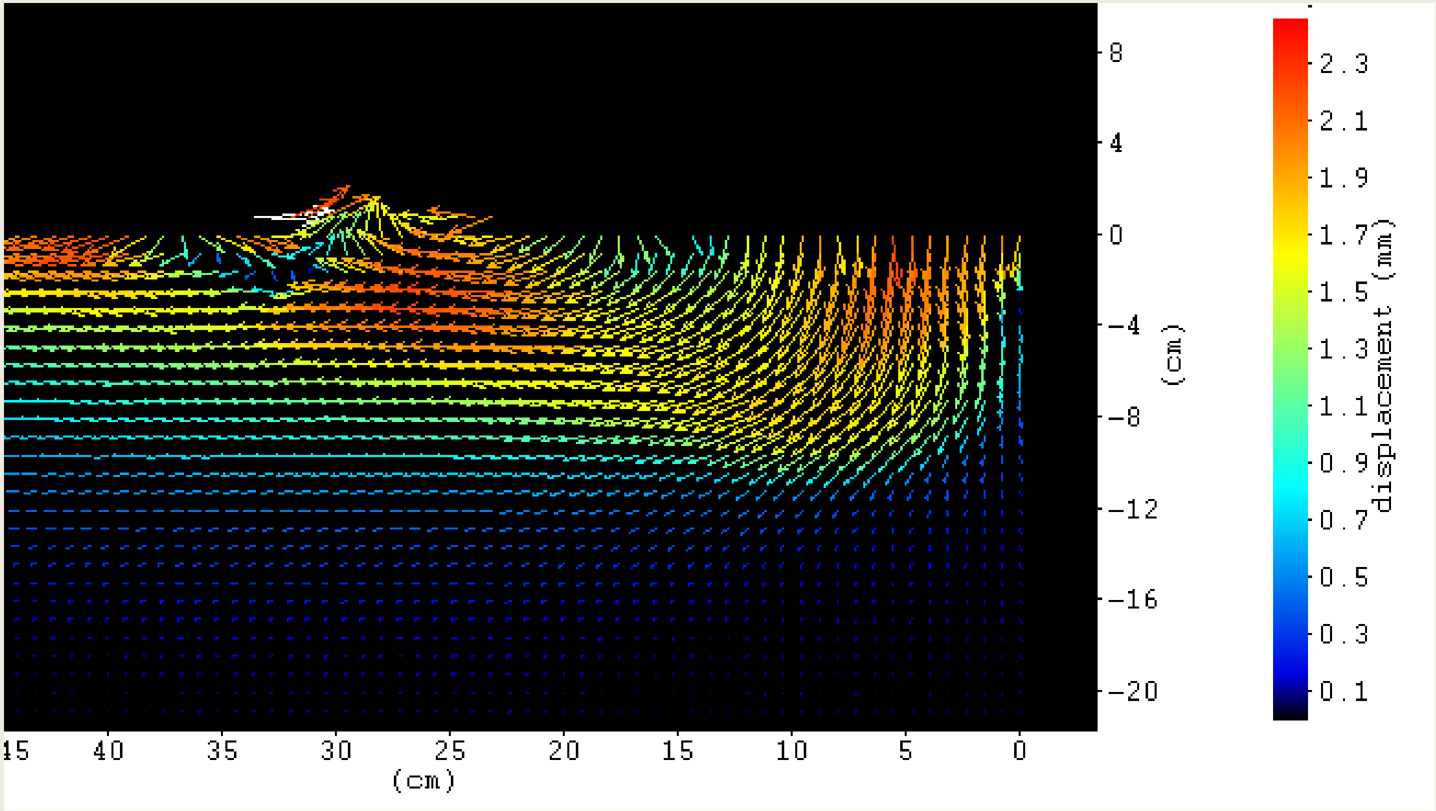




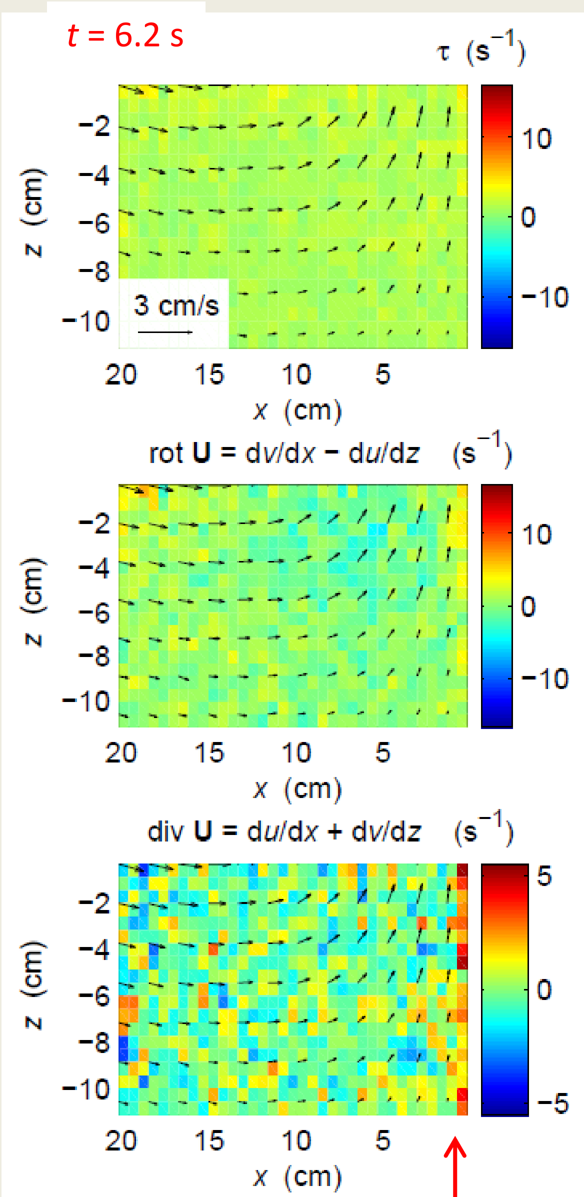
Analysis of sand grain displacements during wave impact

Acquisition frequency : 30 Hz
1272 x 1016 pixels ---> 30 cm x 20 cm
'Davis' LaVision software
correlation window 16 x 16 pixels





Sand grain velocity fields

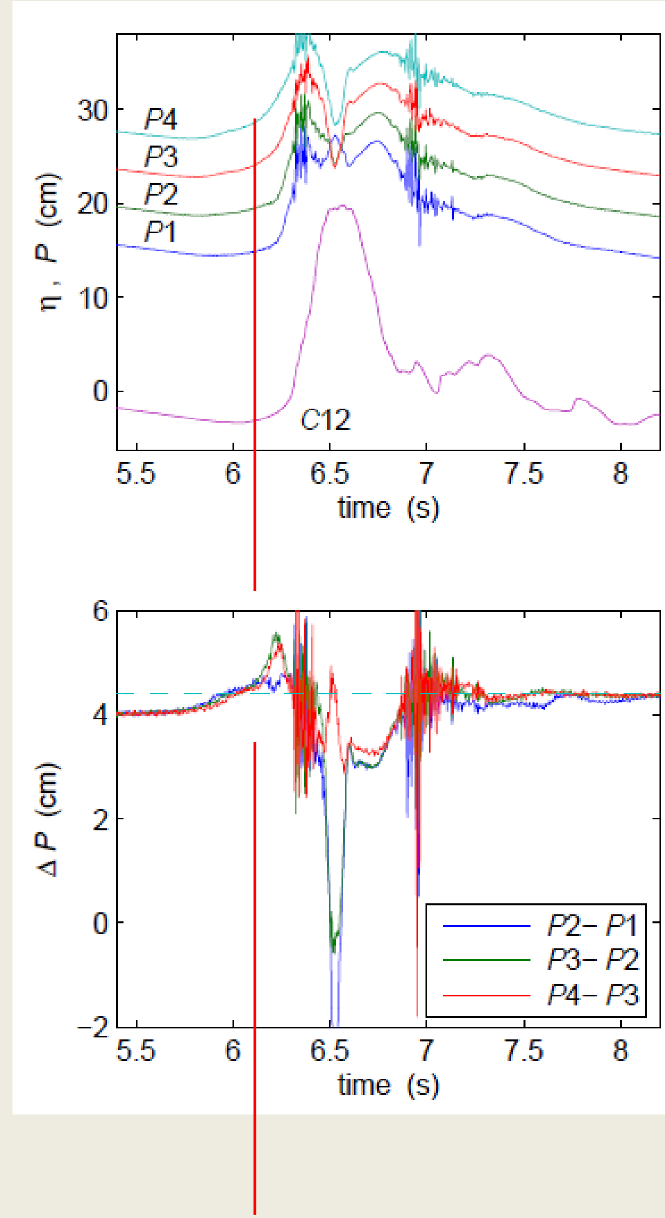


shear stress modulus

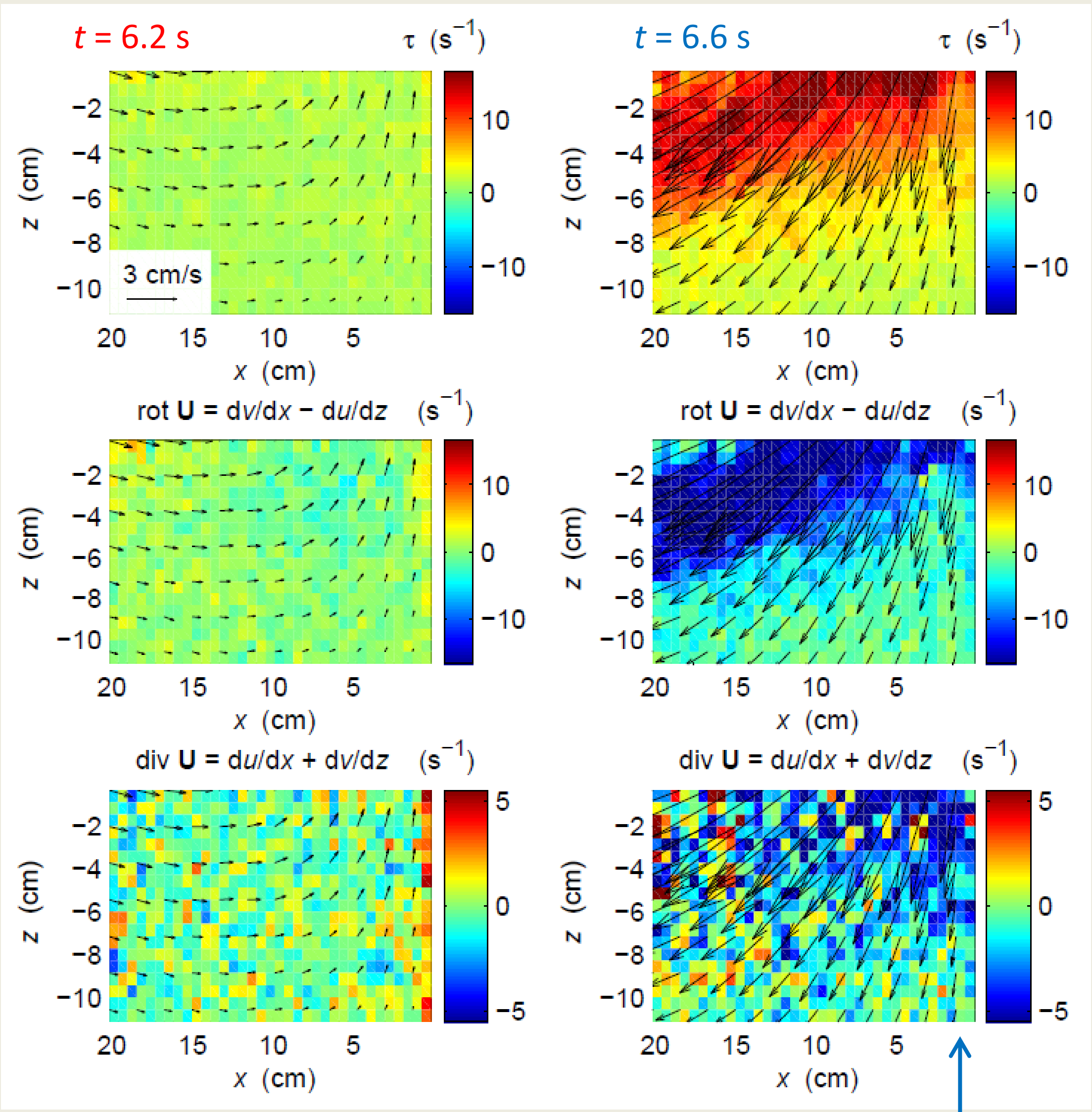
velocity curl

velocity divergence

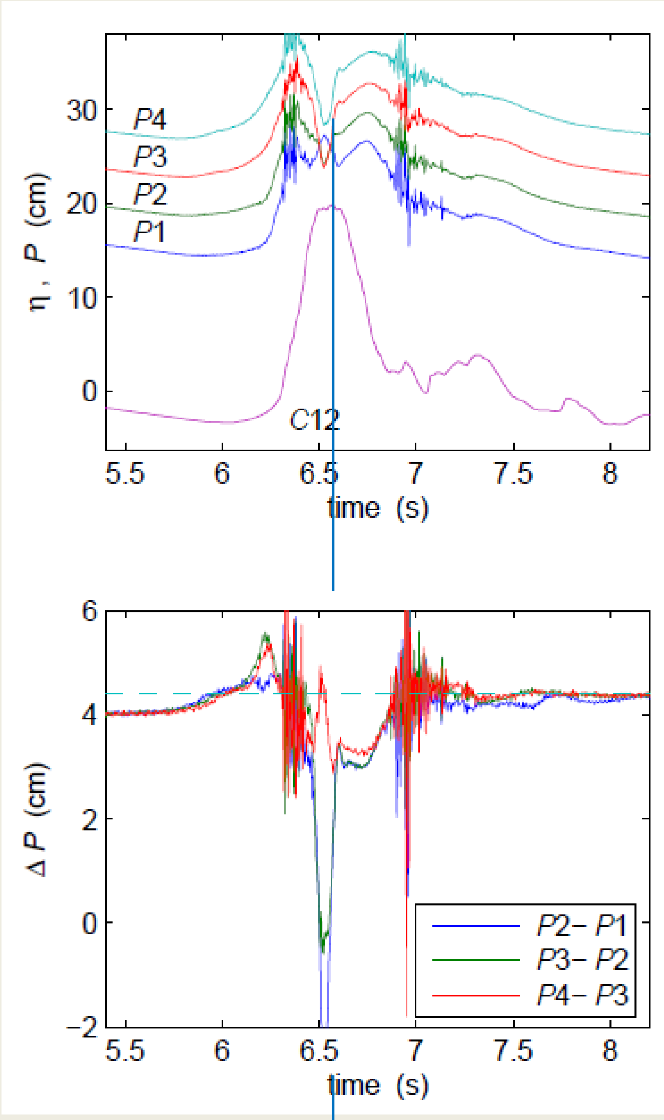
dilatation



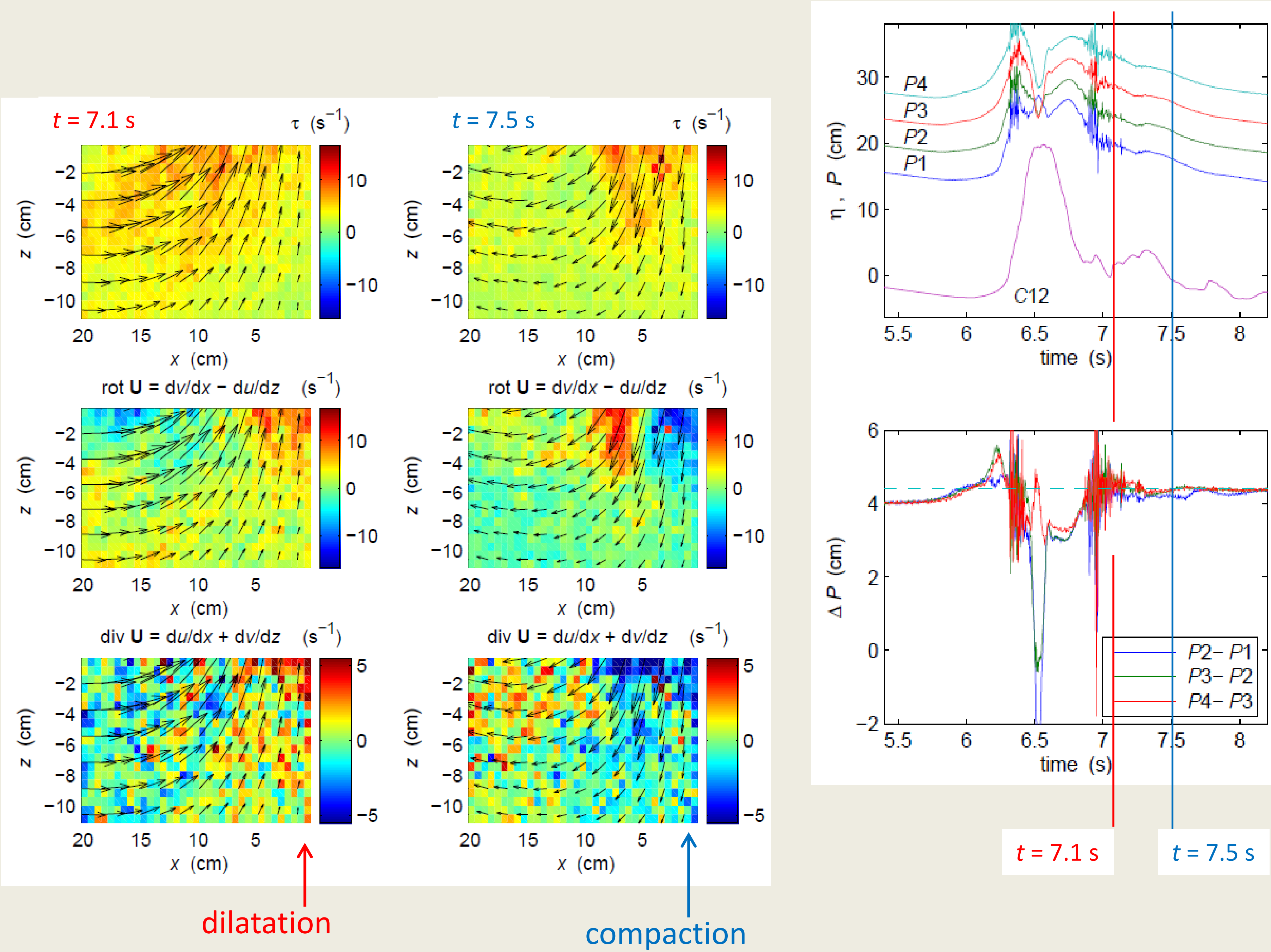
t = 6.2 s



compaction



t = 6.6 s



t = 7.1 s
τ (s⁻¹)
t = 7.5 s
rot U = dv/dx − du/dz (s⁻¹)
div U = du/dx + dv/dz (s⁻¹)
z (cm)
x (cm)
dilatation
compaction
P4
P3
P2
P1
C12
η , P (cm)
time (s)
Δ P (cm)
P2− P1
P3− P2
P4− P3
t = 7.1 s
t = 7.5 s

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(coll. 3S-R lab.: B. Chareyre, L. Scholtes, E. Catalano)

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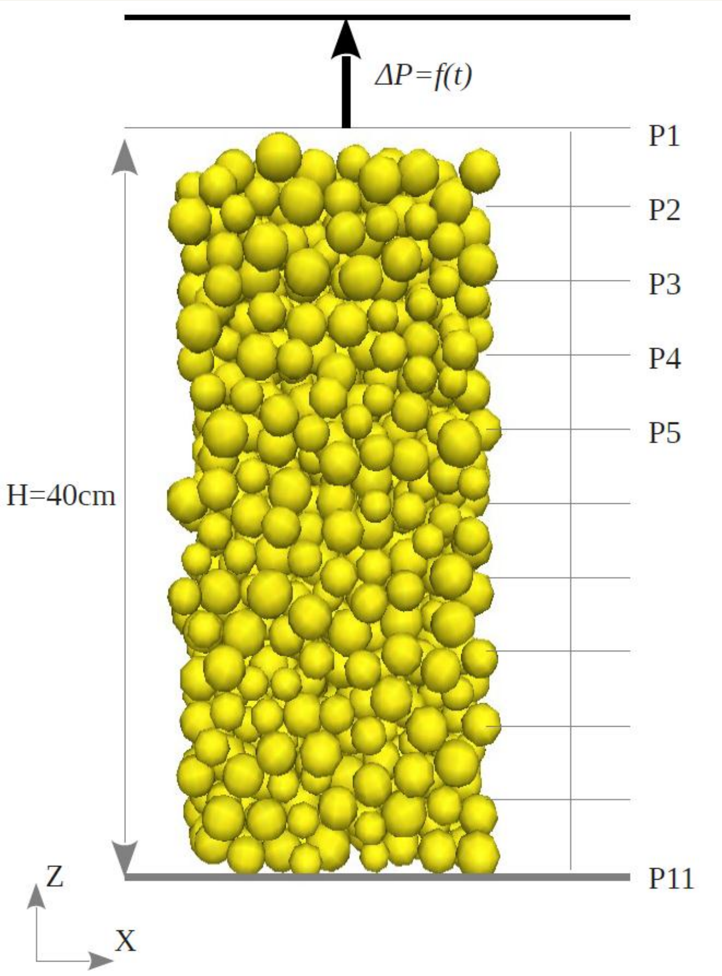
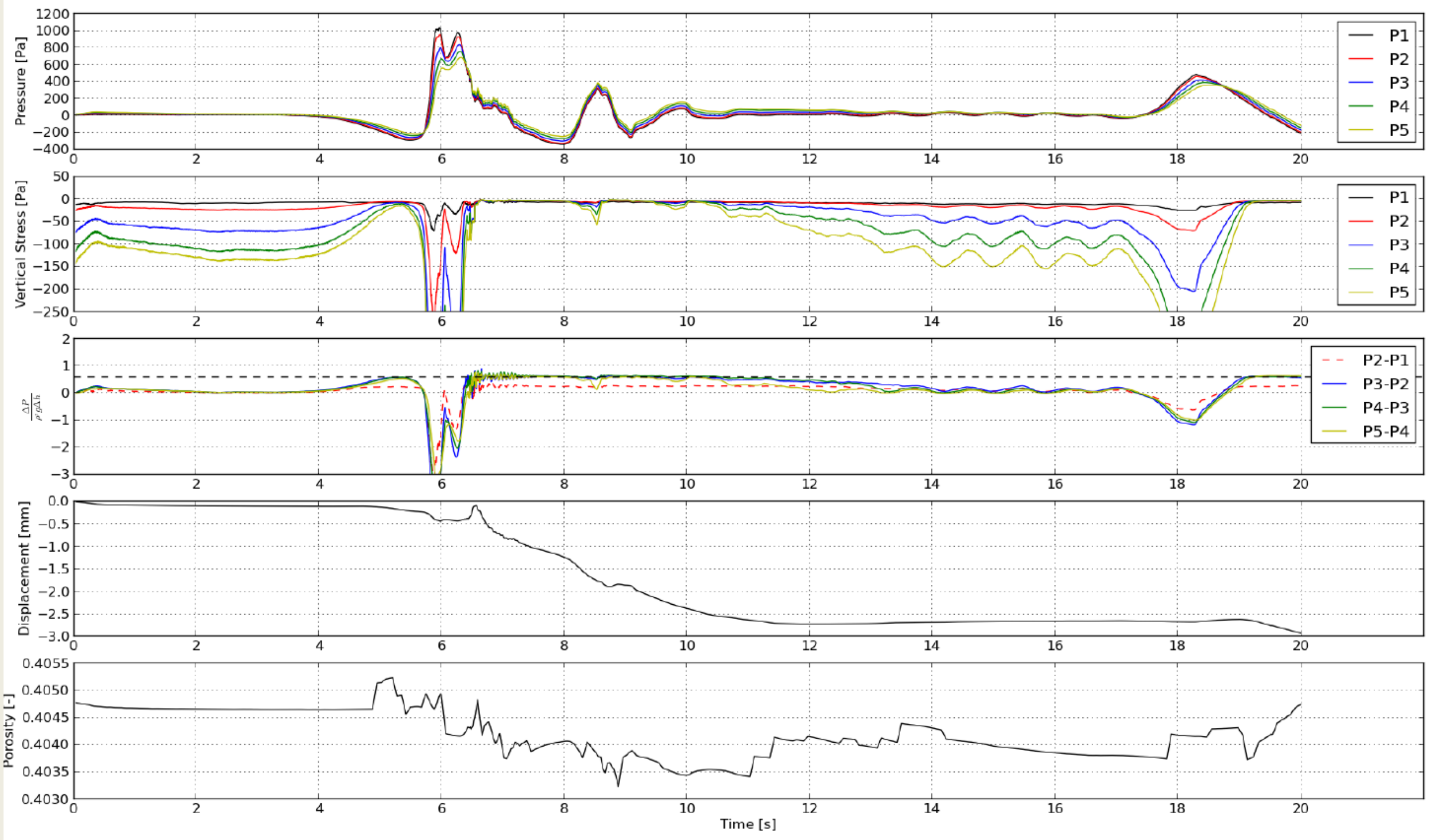
Thank you for your attention !

DEM numerical modeling (Grenoble - 3S-R)

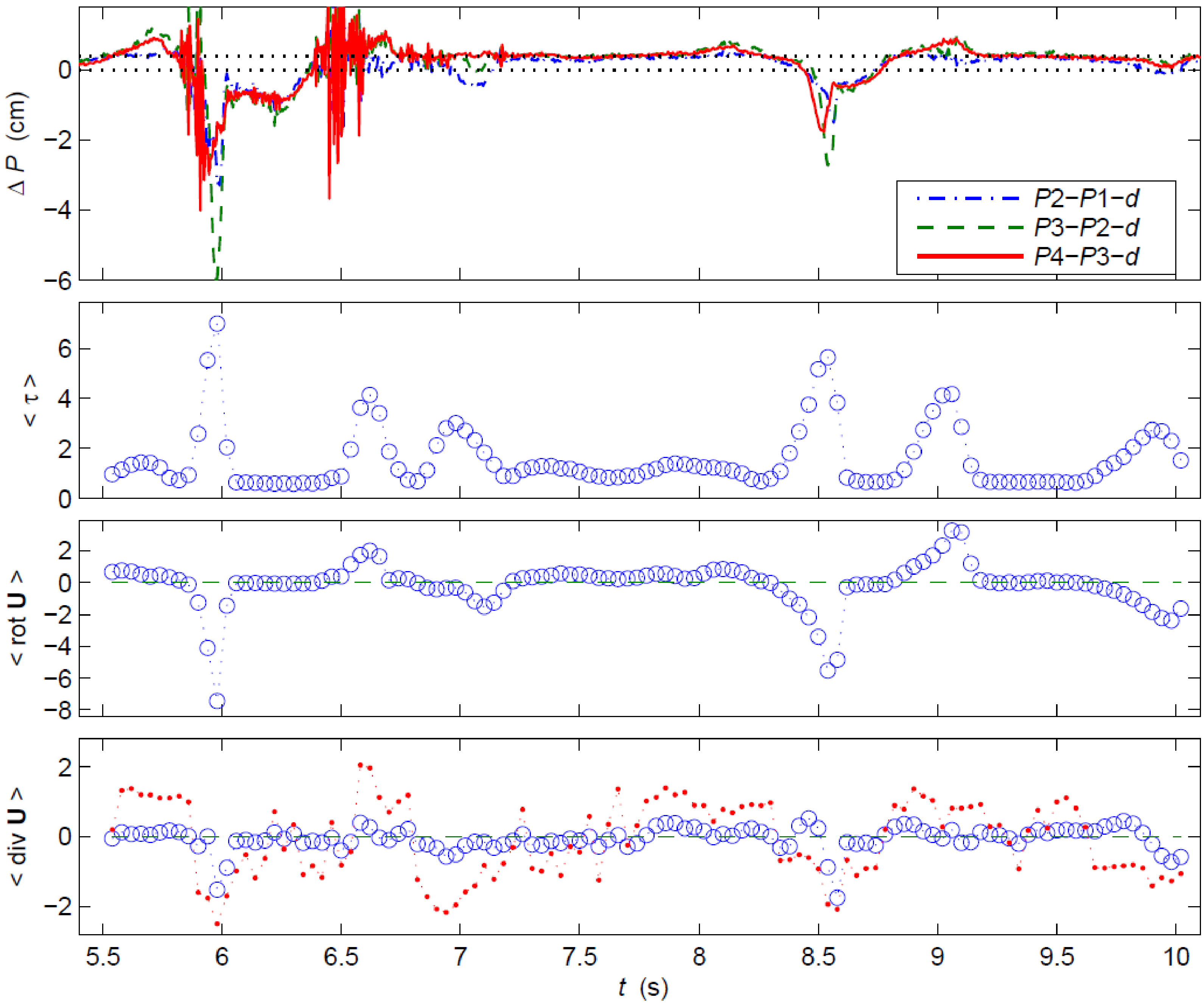
L. Scholtes, E. Catalano, B. Chareyre



REFERENCE NUMERICAL SAMPLE :
1000 grains : bi-periodic boundary conditions (X,Y)
Density=1100 kg/m^3
Dmean=2.6 cm
porosity : n = 0,404
Mechanical properties :
Young's modulus : E ~ 3,1 MPa
bulk Modulus B ~ 1,9 MPa
Poisson's ratio : υ ~ 0,225
shear modulus : G ~ 1,3 MPa
Hydraulic properties :
hydraulic conducitvity : K~ 3e-3 m/s



Pressure [Pa]
1200
1000
800
600
400
200
0
−200
−400
P1
P2
P3
P4
P5
Vertical Stress [Pa]
50
0
−50
−100
−150
−200
−250
$\frac{\Delta P}{\rho g \Delta h}$
2
1
0
−1
−2
−3
P2-P1
P3-P2
P4-P3
P5-P4
Displacement [mm]
0.0
−0.5
−1.0
−1.5
−2.0
−2.5
−3.0
Porosity [-]
0.4055
0.4050
0.4045
0.4040
0.4035
0.4030
0
2
4
6
8
10
12
14
16
18
20
Time [s]

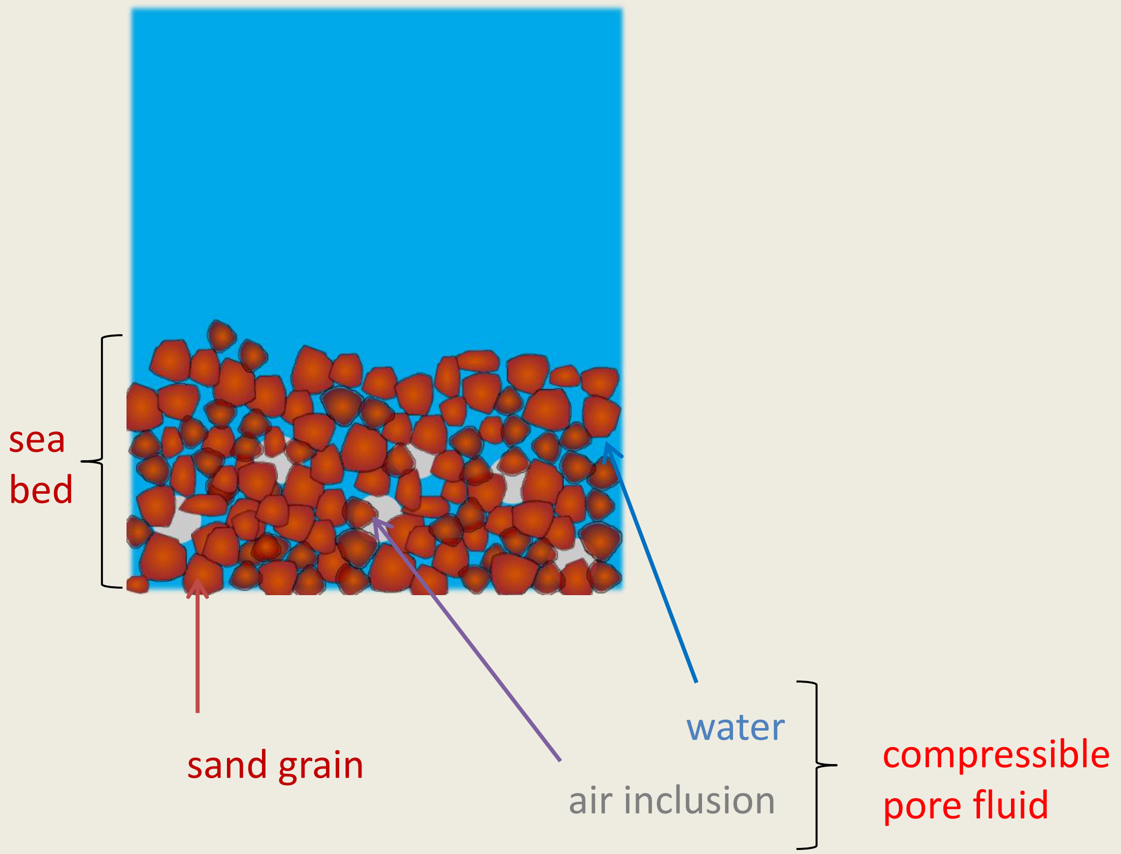


Δ P (cm)
P2−P1−d
P3−P2−d
P4−P3−d
< τ >
< rot **U** >
< div **U** >
t (s)

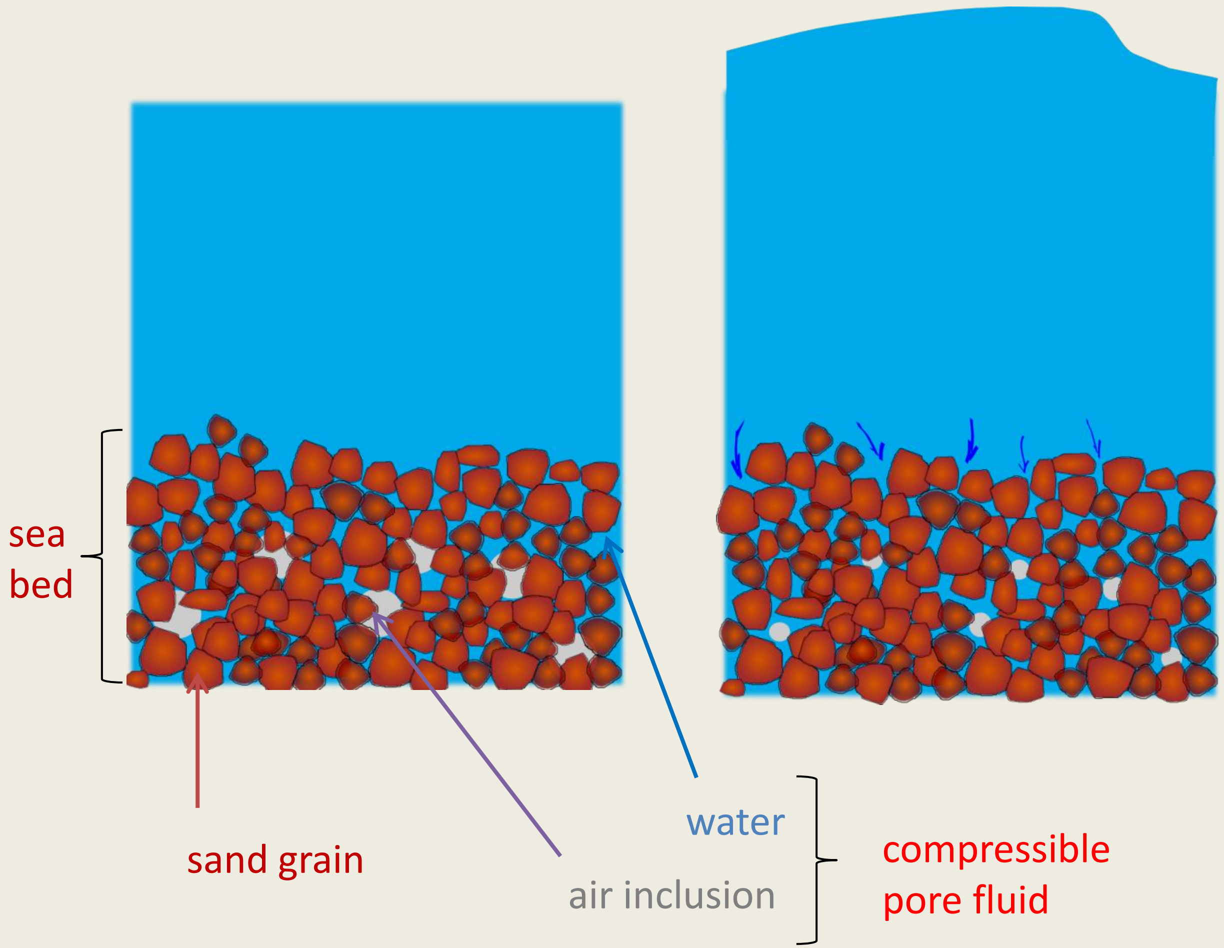
Norme du tenseur de cisaillement

$$\| \dot{\overline{\overline{\gamma}}} \| = \sqrt{\frac{1}{2}\left[\frac{\partial u}{\partial x}^2 + \frac{\partial w}{\partial z}^2\right] + \frac{1}{4}\left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2}$$

Wave induced liquefaction

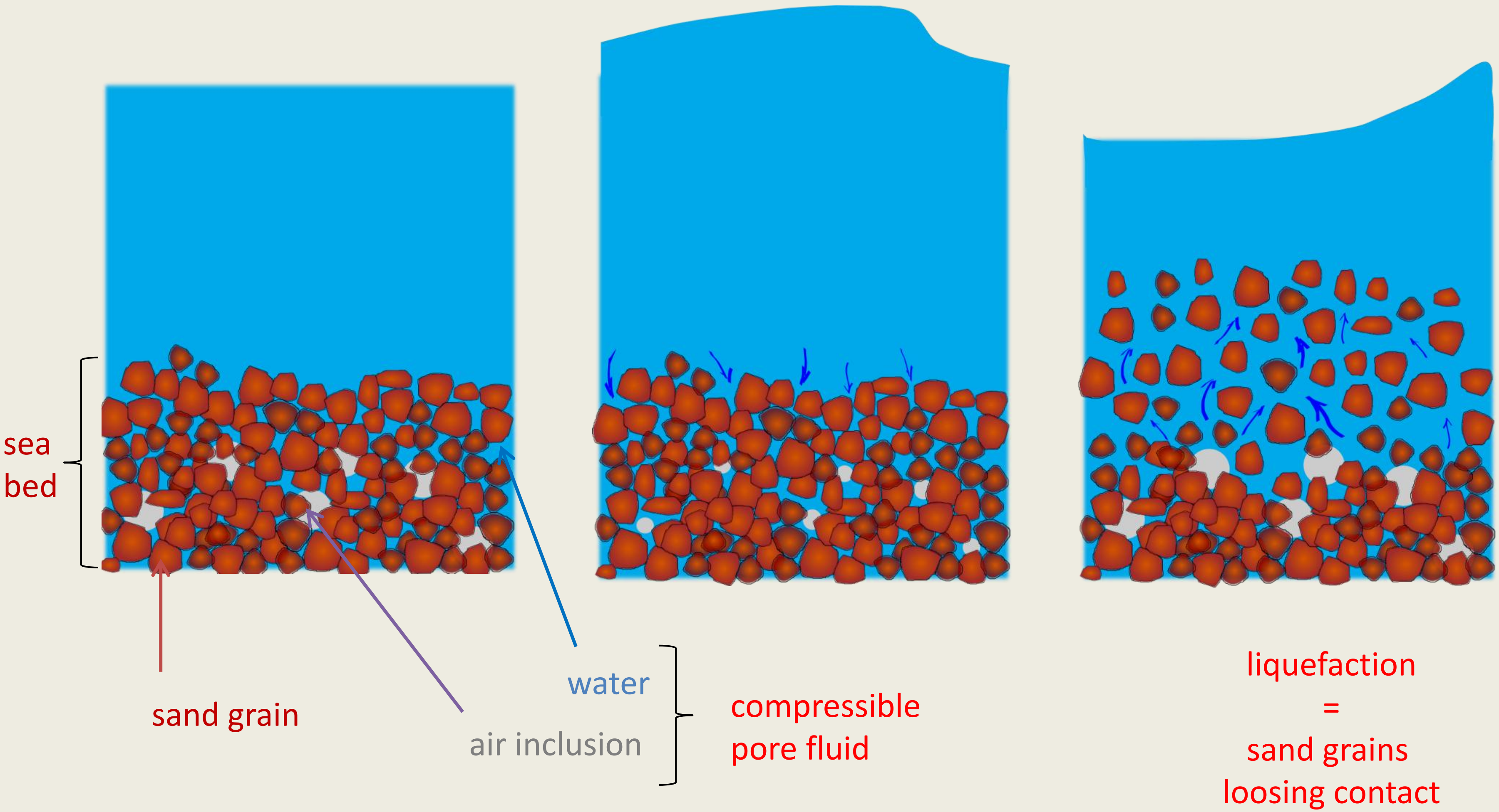


Wave induced liquefaction



due to phase lag in pressure transmission into the bed (Mei and Foda, 1981; Sakai et al, 1992; …)

Wave induced liquefaction



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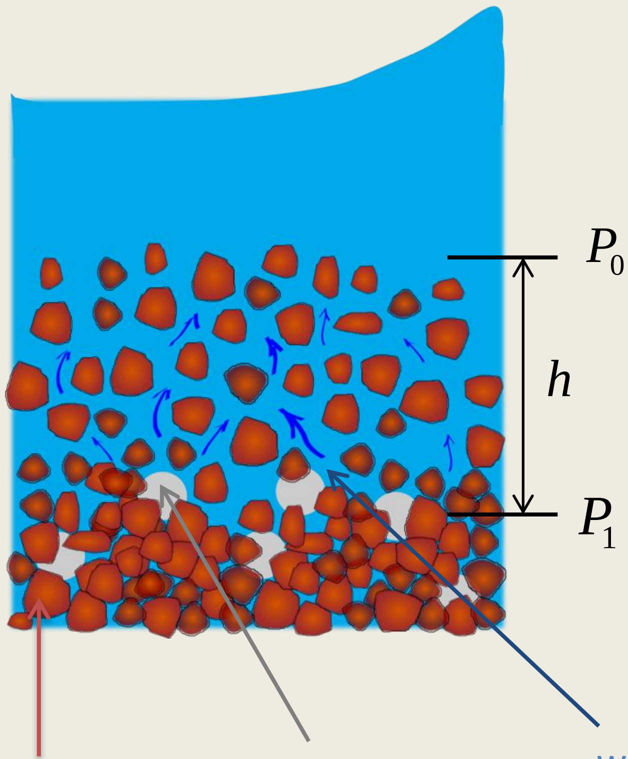


Liquefaction threshold
=
pore pressure exceeding the soil weight

$$\frac{P_1 - P_0}{\rho g} > h\left[\frac{\rho_s}{\rho}(1-n) + n - n\,C_g\left(1 - \frac{\rho_s}{\rho}\right)\right]$$

n = bed porosity

C_g = gas content

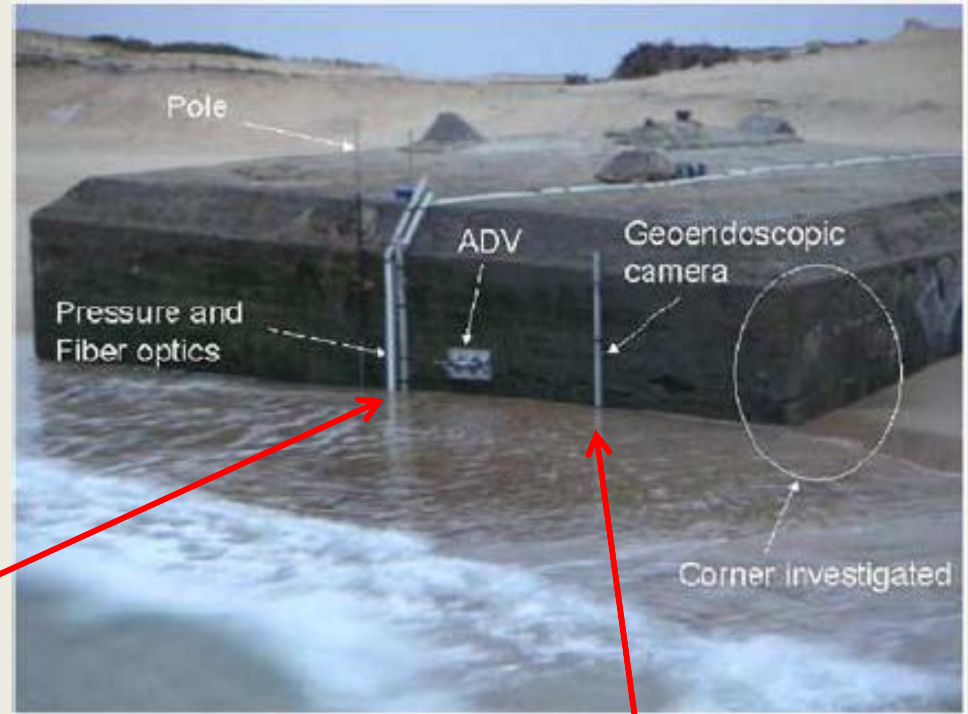
From EC-FP5 LIMAS project:

Field evidence of liquefaction occurrence

induced by wave impact on a coastal structure

Mory et al. (2007)
Michallet et al. (2009)

Pore pressure measurements, estimation of the sand bed level



Geo-endoscopic video camera for estimation of the soil gas content

Breul et al. (2008)

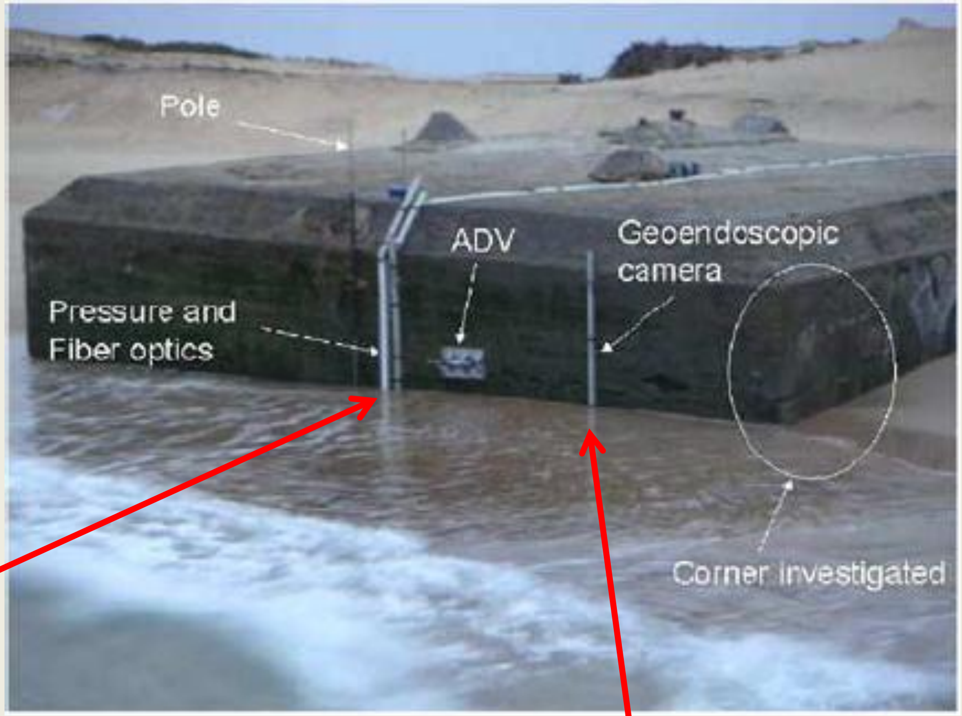
$$C_{gas} \sim 0.1\% \text{ to } 8\%$$

From EC-FP5 LIMAS project:

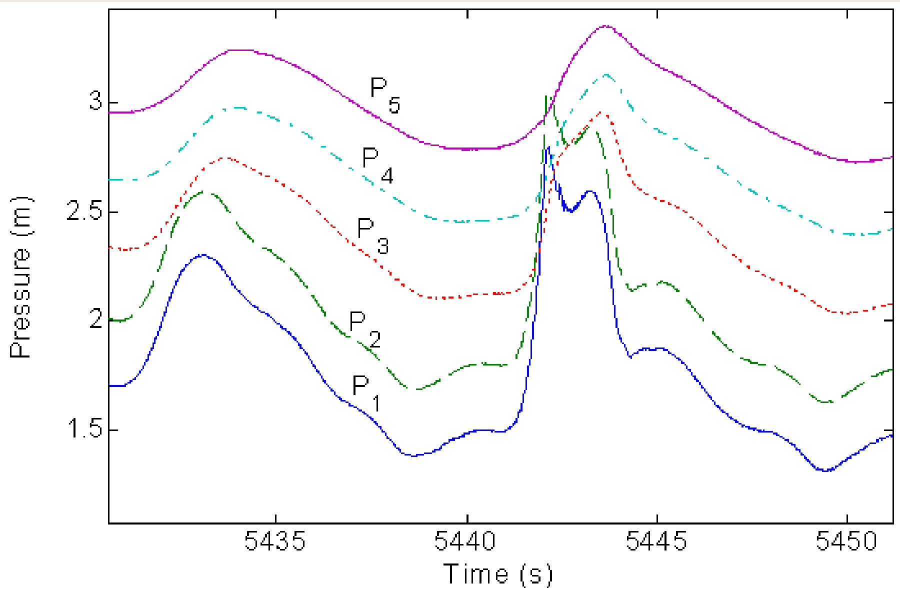
Field evidence of liquefaction occurrence

induced by wave impact on a coastal structure

Mory et al. (2007)
Michallet et al. (2009)



Pore pressure measurements, estimation of the sand bed level



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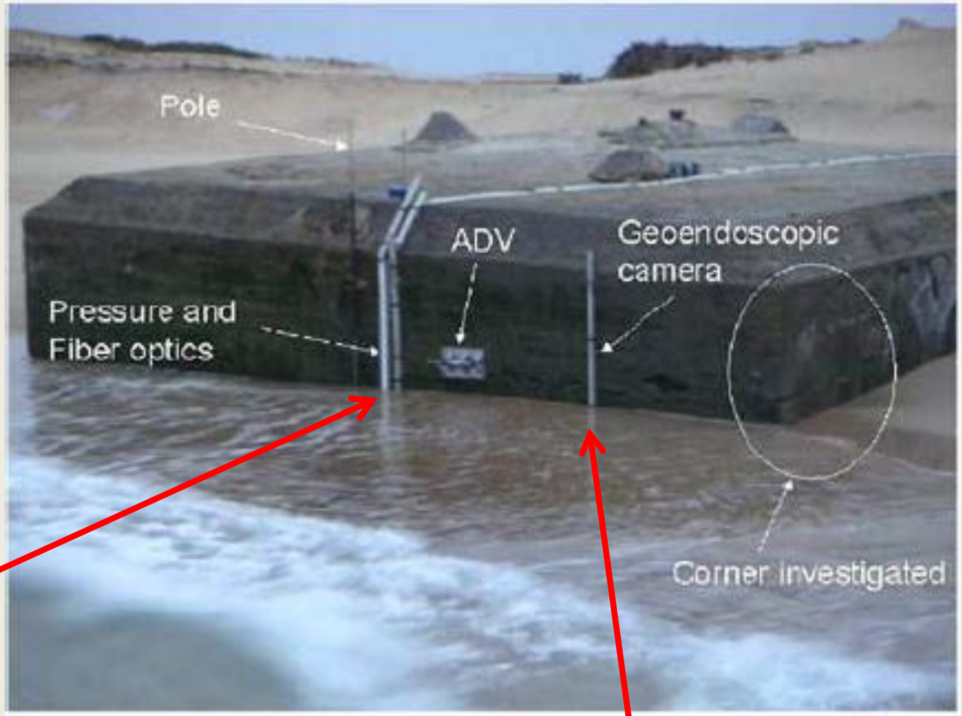

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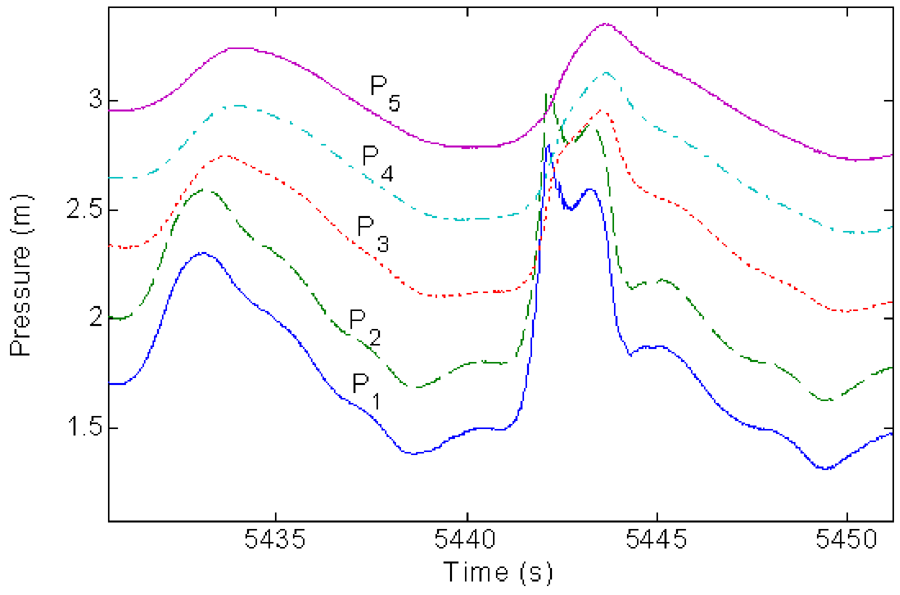

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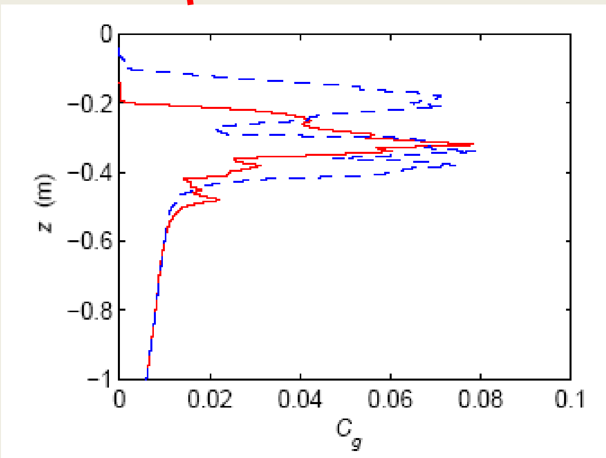

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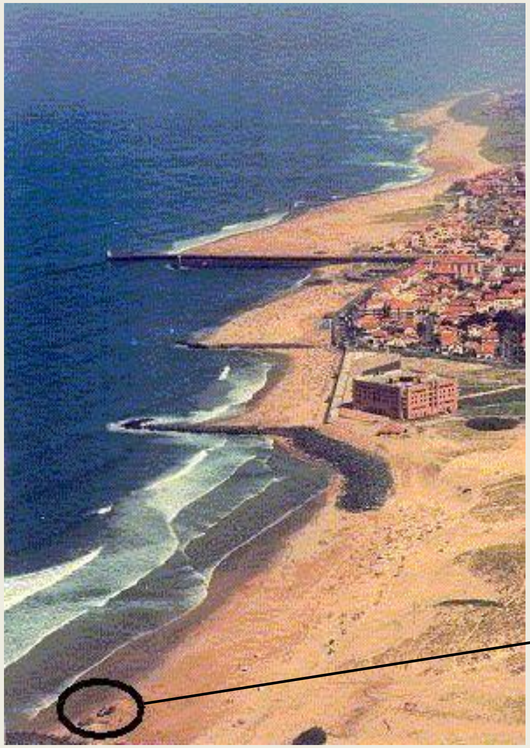
"Liquefaction Around Marine Structures" (LIMAS – EC FP5)

- Field measurements of pore pressure transmission within the sand bed and induced liquefaction under wave action
- Influence and quantification of the soil gas content

Mory et al., 2007

Breul, Hadani & Gourvès, 2008

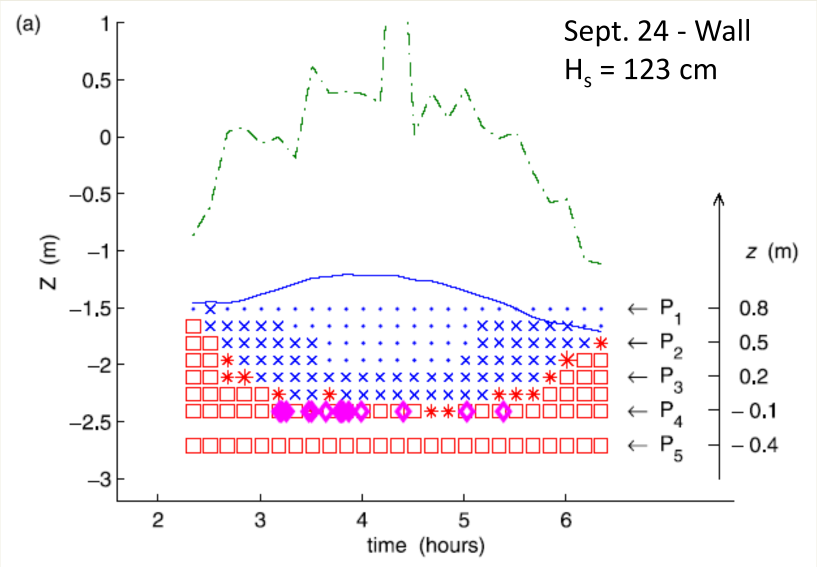
Michallet, Mory & Piedra Cueva, 2009

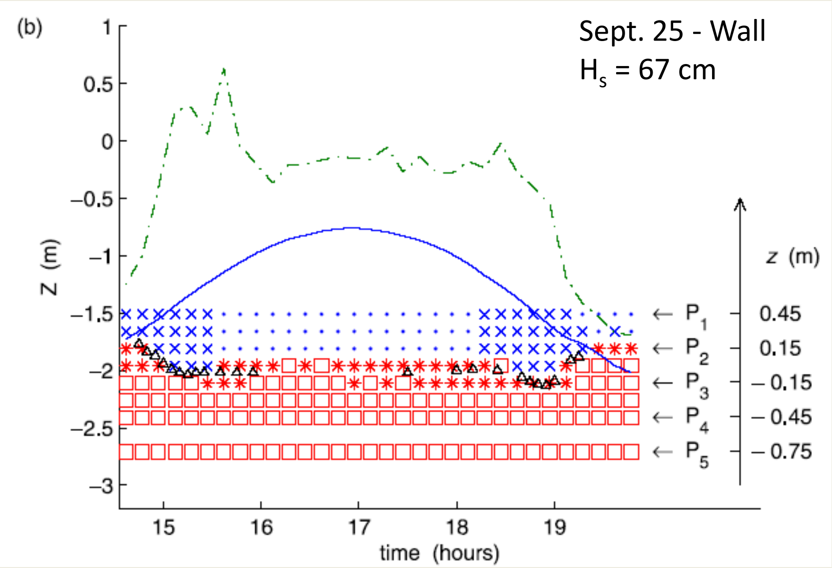


Capbreton, Atlantic Ocean, France

Wave breaking on the instrumented bunker

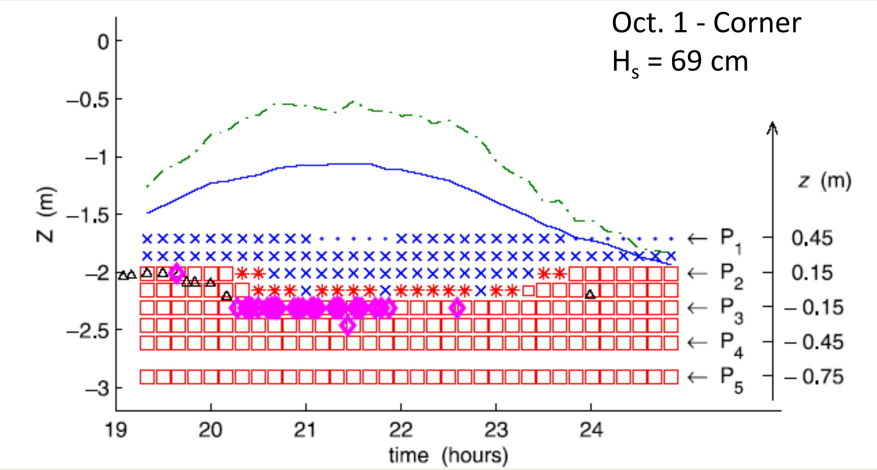
Bed changes during a tidal period





Erosion produced by waves on the wall during rising tide

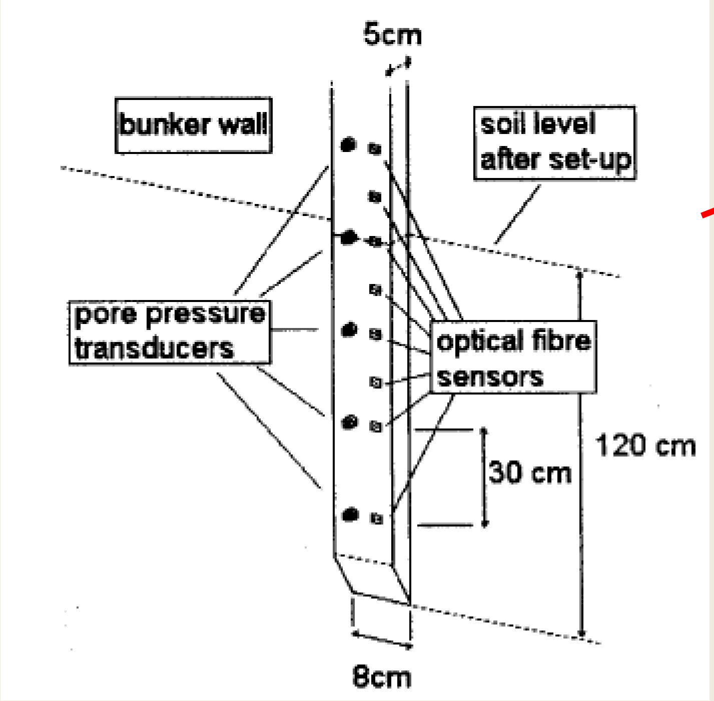
Sediment deposition at the end of the tidal period

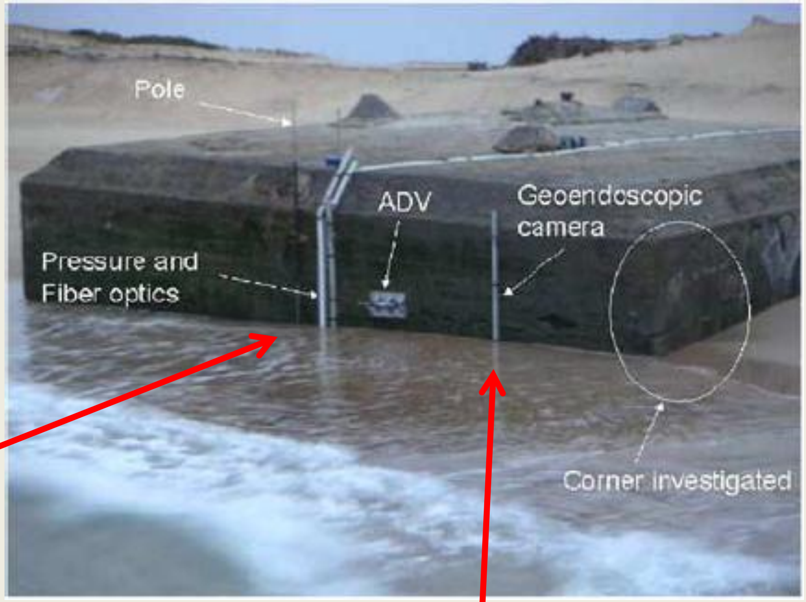


Instrumentation

Pore pressure measurements

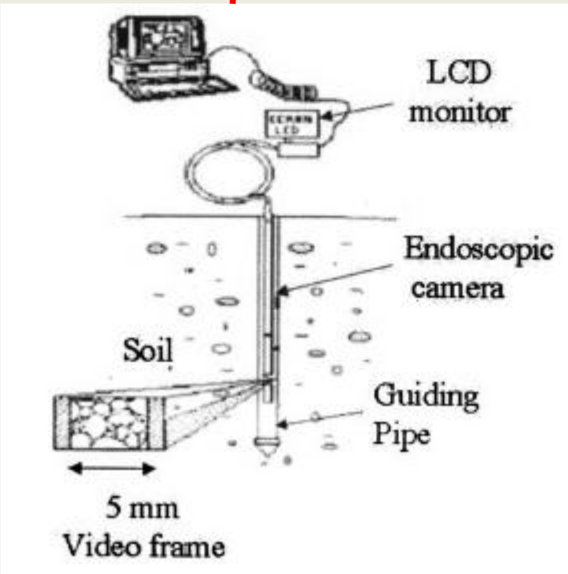
and estimation of the sand bed level





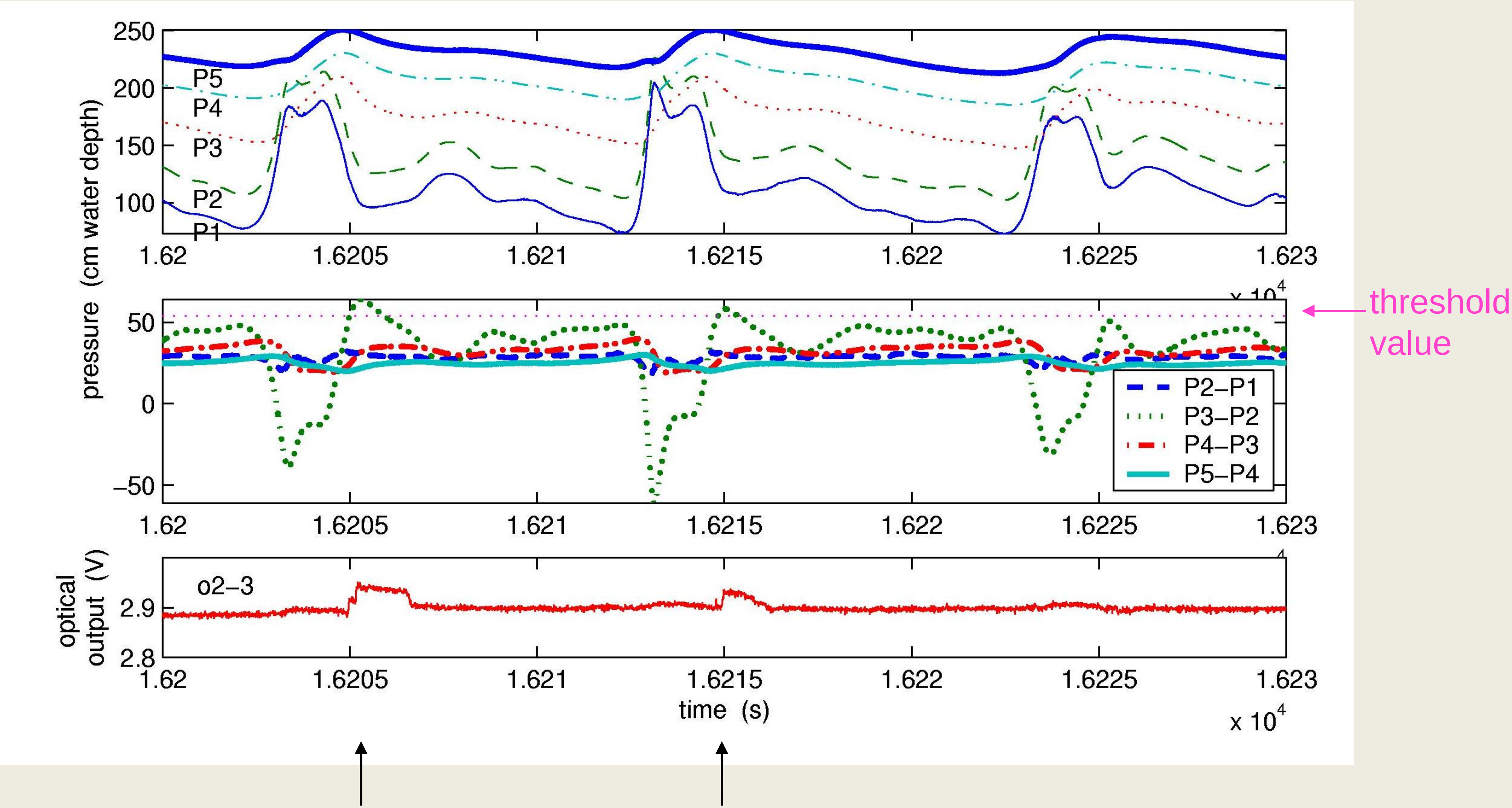
Geo-endoscopic video camera for estimation of the soil gas content

Sol Solution / LAMI



Liquefaction threshold

$$\frac{\Delta P_{i,i-1}}{\rho g} = \frac{P_i - P_{i-1}}{\rho g} > h\left[\frac{\rho_s}{\rho}(1-n)+n-nC_g\left(1-\frac{\rho_s}{\rho}\right)\right]$$



Pressure difference P3 – P2 over-critical
in phase with optical sensor response → soil mobility !!

Effect of gas content on the transmission of pressure variations inside the soil

Mei & Foda, 1981
Sakai, Hatanaka & Mase, 1992

$$\frac{P(z)}{P_0} = \left[\frac{1}{1+m}\mathrm{e}^{-\lambda z} + \frac{m}{1+m}\mathrm{e}^{(\mathrm{i}-1)z/\sqrt{2}\delta}\right]\mathrm{e}^{\mathrm{i}(\lambda x - \sigma t)}$$

$$m = \frac{n}{1-2\nu}\frac{G}{\beta}$$

$$\delta = \left(\frac{k}{\rho g}\frac{G}{\sigma}\right)^{1/2}\left[\frac{nG}{\beta} + \frac{1-2\nu}{2(1-\nu)}\right]^{-1/2}$$

Vertical profiles of damping of pore pressure indicate the vertical variation of the gas content inside the bed

Effective bulk modulus of pore water

$$\frac{1}{\beta} = \frac{1}{\beta_w} + \frac{C_{gas}}{P_{ref}}$$

No gas

$\beta \gg G$

$m \ll 1$

$$\frac{P(z)P^*(z)}{{P_0}^2} = \mathrm{e}^{-2\lambda z}$$

Gas content in the range $2\times10^{-3} < C_{gas} < 4\times10^{-2}$

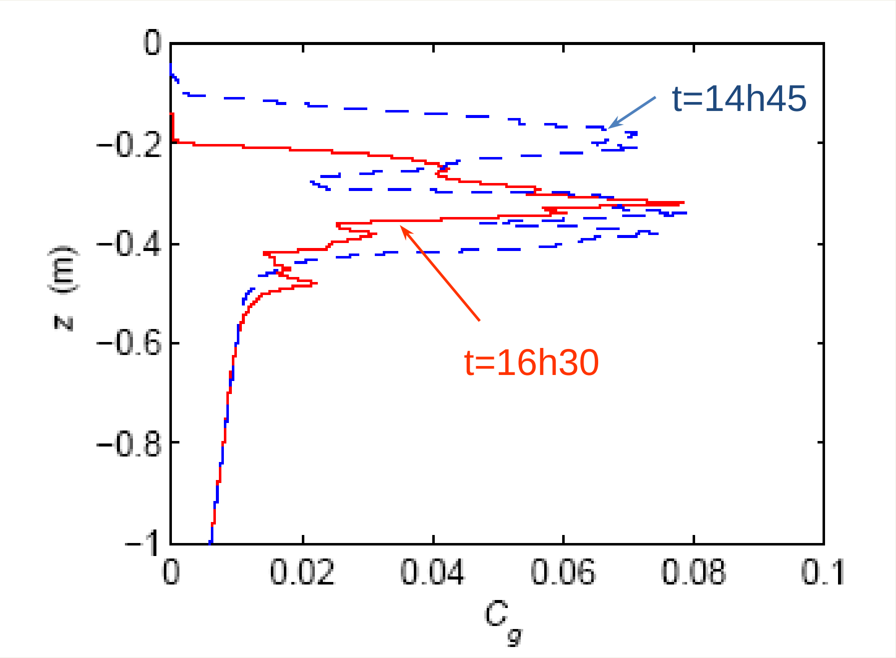
$$\frac{P(z)P^*(z)}{{P_0}^2} = \mathrm{e}^{-\sqrt{2}z/\delta}$$

$$\frac{{P_i}^2(f)}{{P_{i-1}}^2(f)} = \mathrm{e}^{-\sqrt{2}(z_i - z_{i-1})/\delta}$$

Vertical profiles of gas content inside the soil measured by a geoendoscopic camera

(Breul, Hadani & Gourvès, 2008)

Sept. 25, 2003



Gas has escaped from the upper soil layer during rising tide

Vertical profiles of gas content inside the soil measured by a geoendoscopic camera

(Breul, Hadani & Gourvès, 2008)

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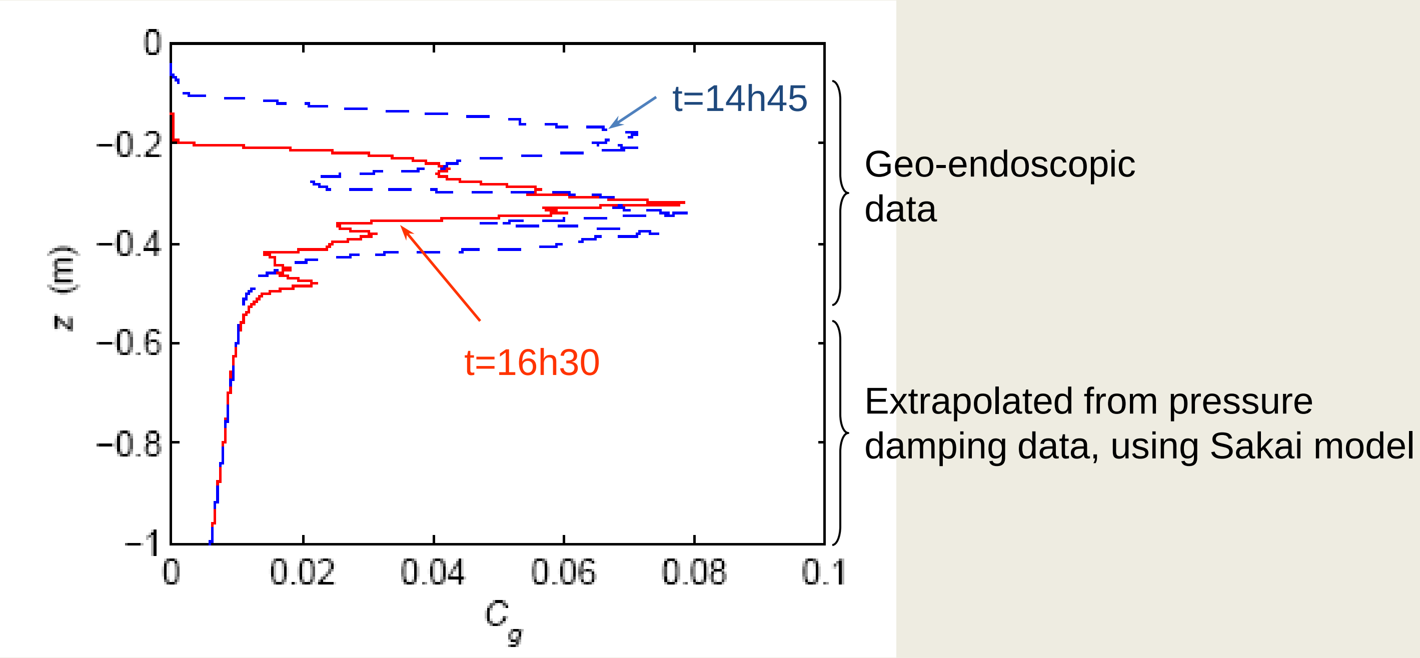
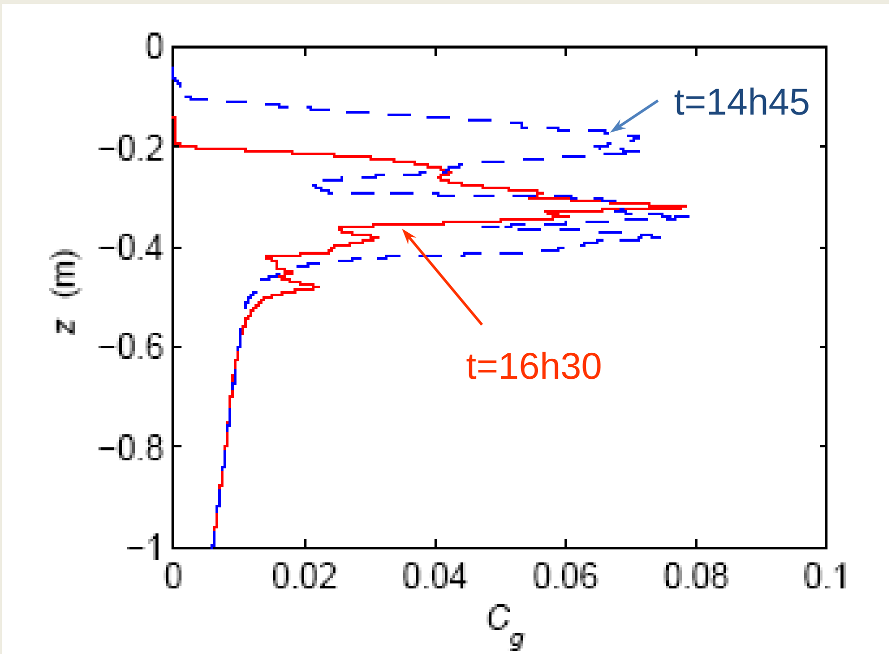


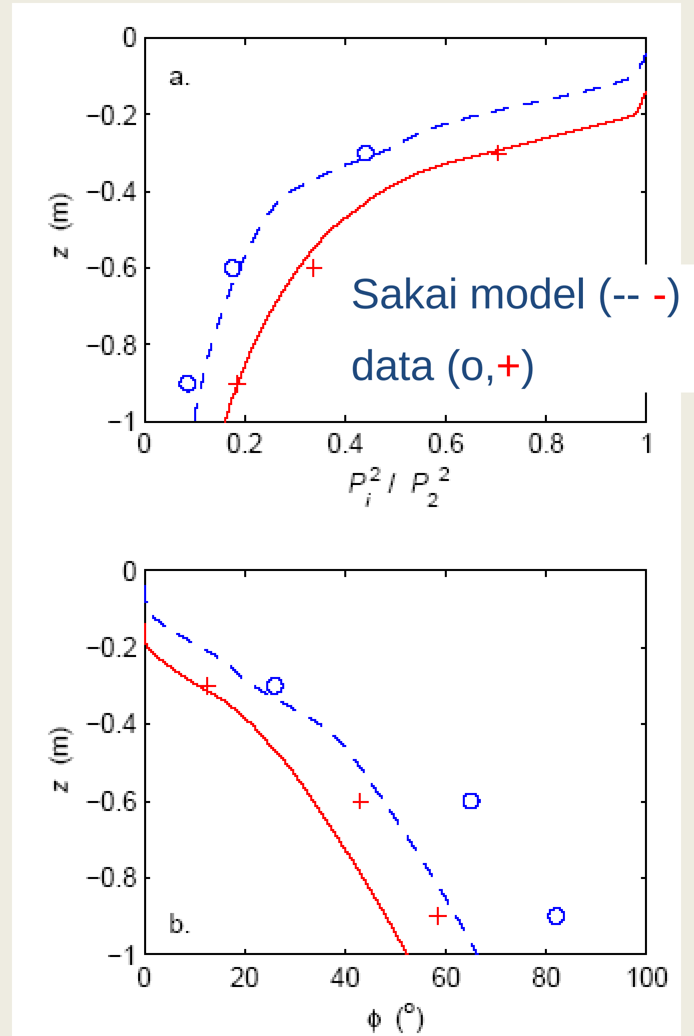
Gas has escaped from the upper soil layer during rising tide

Intercomparison measurements / Sakai model :
pressure damping / phase lags

(Michallet, Mory & Piedra-Cueva, 2009)

Sept. 25, 2003

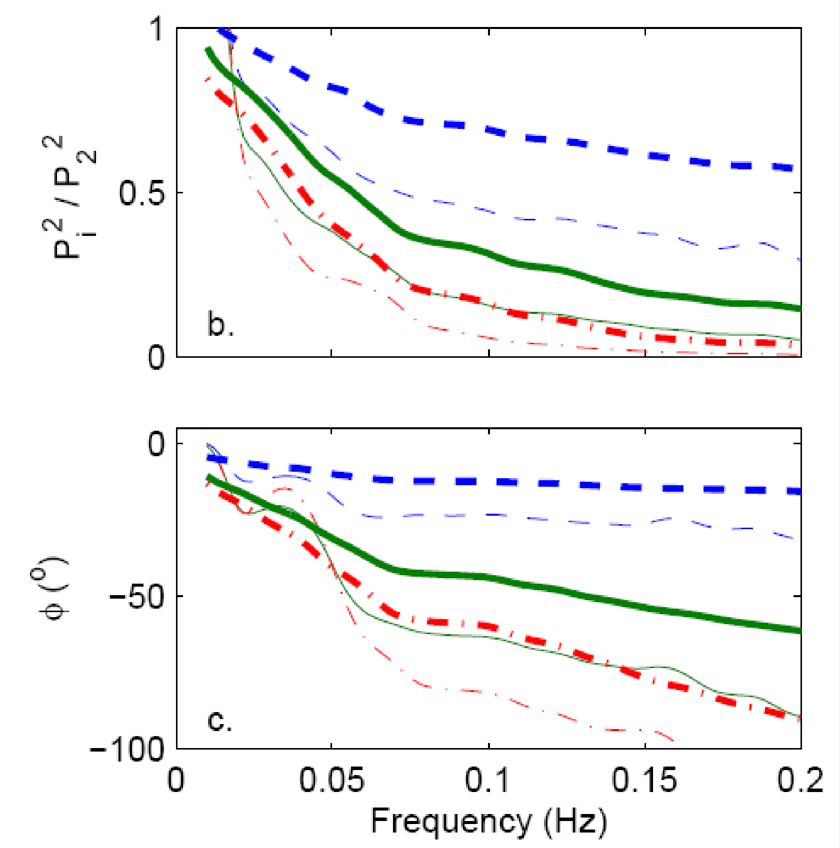




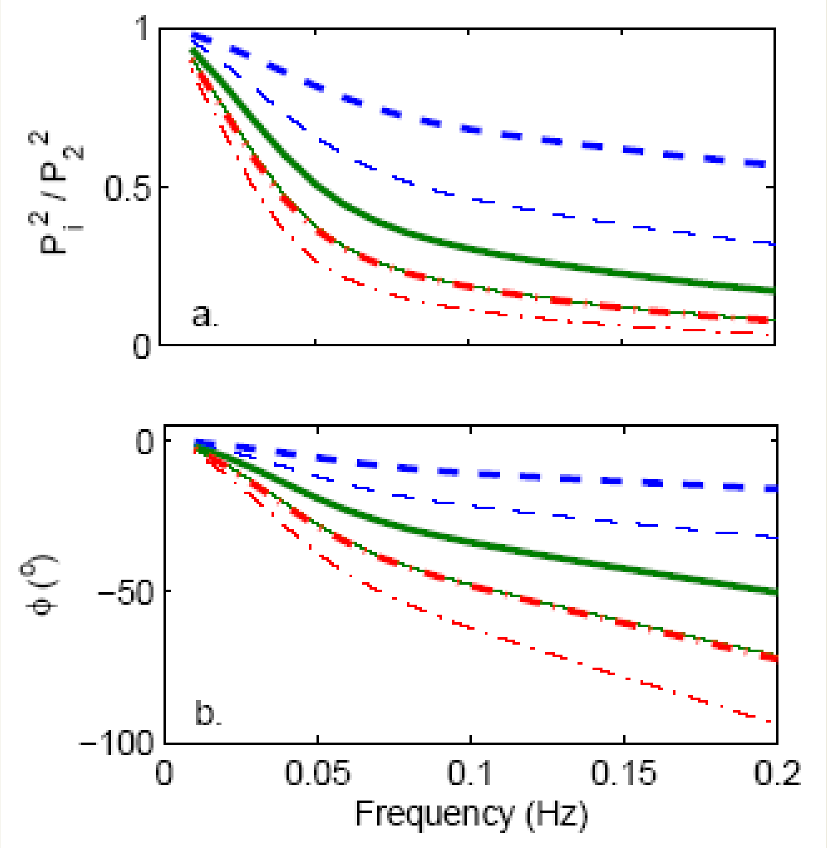
Gas has escaped from the upper soil layer during rising tide
that largely changes pressure transmission in the soil !!

Damping and phase shift against wave frequency

Measurements



Sakai et al. model



Sept. 25, 2003

thin lines: t=14h45

bold lines: t=16h30

Physical model

length scale ~ 1/10
time scale ~ 1/3

Shields scaling

$$\theta = \frac{u_\star^2}{(\rho_s/\rho - 1)\, g\, d_{50}}$$

Rouse scaling

$$Rou = \frac{w_s}{u'}$$

Light-weight sediment
ρ_s = 1.19 g/cm^3
d_{50}= 0.6 mm
w_s = 2.1 cm/s

F. Grasso, C. Berni …