Field observations of momentary liquefaction produced by waves when air is trapped inside a sandy soil

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- Transmission of pressure variations inside the soil
- Momentary liquefaction caused by waves in a sandy soil
- Liquefaction by build up of pore pressure in fine sediments

Compressibility of a air-water mixture

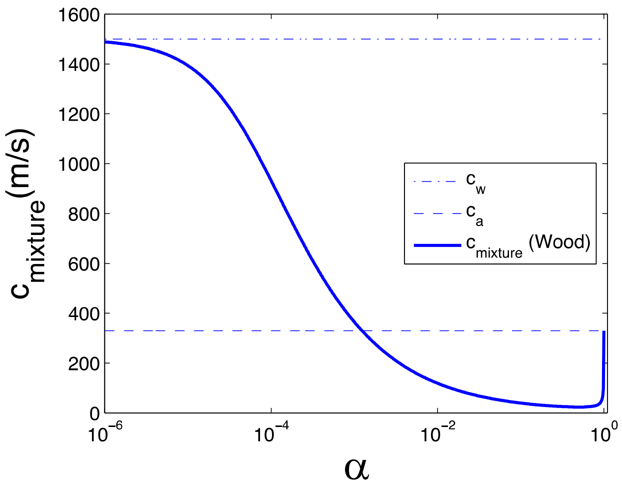
(homogeneous dispersion of micro-bubbles in water)

α volume gas content

$$\rho = \rho_{water}(1-\alpha) + \rho_{air}\alpha$$

Relation between compressibility and sound speed

$$\chi = -\frac{\partial V}{V\partial P} = \frac{\partial \rho}{\rho \partial P} = \frac{1}{\rho c^2}$$



Wood's law

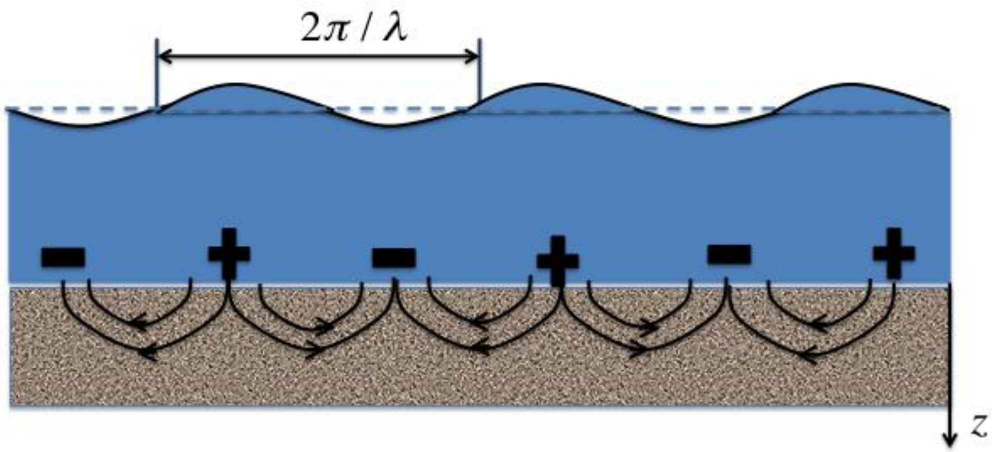
$$\chi = \frac{1}{\rho c^2} = \left\{ \frac{1-\alpha}{\rho_{water} c_{water}^2} + \frac{\alpha}{\rho_{air} c_{air}^2} \right\}$$

- **High increase of compressibility for small air content**

$$\chi \cong \chi_{water} + \frac{\alpha}{\gamma P_{ref}} \qquad \text{with} \qquad \chi_{water} = 4{,}5\ 10^{-10}\, Pa^{-1}$$

- **Sound speed can reach small values**

Flow in the sandy soil resulting from the high and low pressures applied on the soil by water waves



Pressure variations inside the soil

$$\frac{P(z,x,t)}{P_0} = \left\{ \frac{1}{1+m} e^{-\lambda z} + \frac{m}{1+m} e^{(i-1)z/\delta} \right\} e^{i(\lambda x - \omega t)}$$

$$m = \frac{\varepsilon}{1-2\nu} G c_{fluid} \qquad \delta = \left(\frac{2k}{\mu\omega}\right)^{1/2} \left(\varepsilon c_{fluid} + c_{skel}\right)^{-1/2}$$

Hydrodynamics

Waves: ω, $\lambda(\omega)$, P_0
Viscosity of water: μ
Soil intrinsic permeability: k [m^2]
Soil porosity: ε

Fluid compressibility

Compressibility: χ [Pa^{-1}]
Air content in soil: α
Adiabatic index of dry air : γ

$$c_{fluid} \cong c_{water} + \frac{\alpha}{\gamma P_{ref}}$$

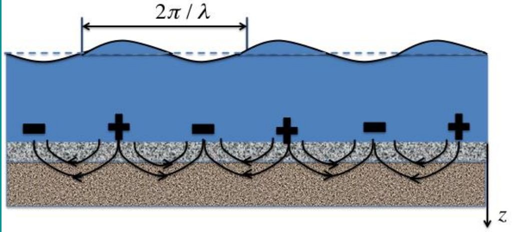
Elastic soil behavior

Shear modulus: G [Pa]
Poisson modulus: ν
Compressibility for 1D restrained deformation of skeleton: χ_{skel}

$$c_{skel} = \frac{1-2\nu}{2(1-\nu)} \frac{1}{G}$$

Mei & Foda, Geophys. JR Astron S.,1981
Sakai, Hatanaka & Mase, JWPOCE, 1992
Gratiot & Mory, ISOPE Conf, 2000
De Groot et al., JWPOCE, 2006

Flow in the sandy soil resulting from the high and low pressures applied on the soil by water waves



$$\frac{P(z,x,t)}{P_0} = \left\{ \frac{1}{1+m} e^{-\lambda z} + \frac{m}{1+m} e^{(i-1)z/\delta} \right\} e^{i(\lambda x - \omega t)}$$

$$m = \frac{\varepsilon}{1-2n} G \left\{ c_{water} + \frac{\alpha}{\gamma P_{ref}} \right\}$$

Leading term in saturated soil

$$m = \frac{\varepsilon}{1-2n} G c_{water} << 1$$

Slow decrease with increasing depth of pressure variations in the soil

Low vertical pressure gradient

Leading term for low gas content

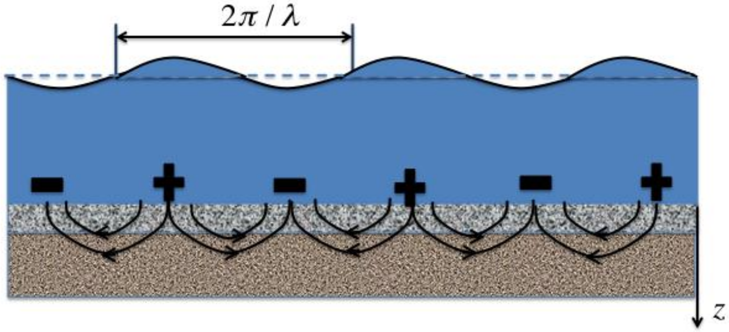
2 10^{-3} < α < 4 10^{-2}

$$m >> 1 \qquad \delta \cong \left(\frac{\gamma P_{ref} k}{m \omega \varepsilon \alpha} \right)^{0,5} << 2\pi / \lambda$$

Independent from elastic properties of the soil skeleton

High vertical pressure gradient

Occurrence of momentary liquefaction



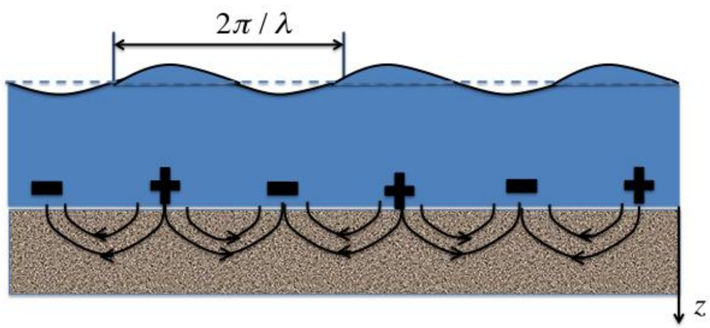
Momentary liquefaction of the sandy soil layer above coordinate z occurs when the pressure gradient exceeds the specific weight

$$P(z,x,t) - P(0,x,t) > \{ r_{sed}(1 - e) + r_{water} e \} gz$$

For usual parameters in coastal areas, high vertical pressure gradient inside the soil – and hence momentary liquefaction - can only be achieved when gas is trapped in the soil

Such conditions are eventually met in intertidal areas on beaches

Occurrence of momentary liquefaction depends on grain size



Momentary liquefaction can only occur in soils of sufficient high grain size, such as sands

Pressure variations need be transmitted over a distance of one wave length λ in a time less than the wave period T_{wave}

Transmission of pressure variations in a porous medium is a diffusive phenomenon with diffusivity coefficient

$$k_{medium} = \frac{k}{m} \frac{1}{c_{medium}} = \frac{k}{m} \frac{1}{\left\{ e c_{fluid} + c_{skel} \right\}}$$

De Groot et al., JWPOCE, 2006

Soil drainage sustains flow variations within a wave period when

$$T_{wave} > \frac{(2p/l)^2}{k_{medium}} = \frac{(2p/l)^2 m}{k} \left\{ e c_{fluid} + c_{skel} \right\} \quad \textbf{or} \quad k > \frac{(2p/l)^2 m}{T_{wave}} \left\{ e c_{fluid} + c_{skel} \right\}$$

i.e. sandy soils

In fine sediments (i.e. silts or mud) liquefaction can result from the build up of pore pressure inside the bed

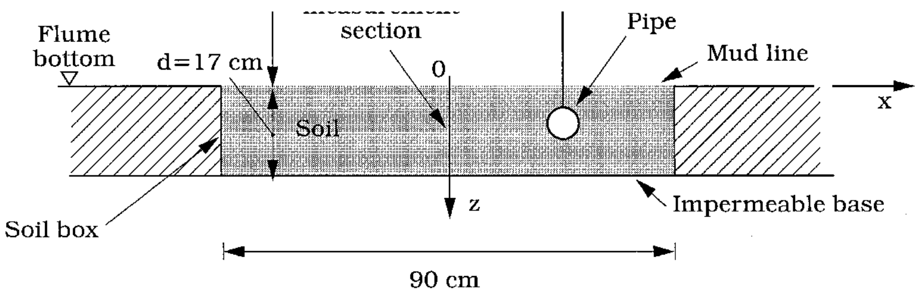
Waves apply cyclic stresses on the soil skeleton, thus producing a contraction of the bed

Pore pressure increases in the soil

Soil drainage is insufficient to release the pore pressure in the soil (residual pore pressure)

De Groot et al., JWPOCE, 2006

Experiments on the floatation of pipelines in liquefied silt soils



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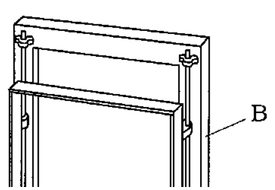
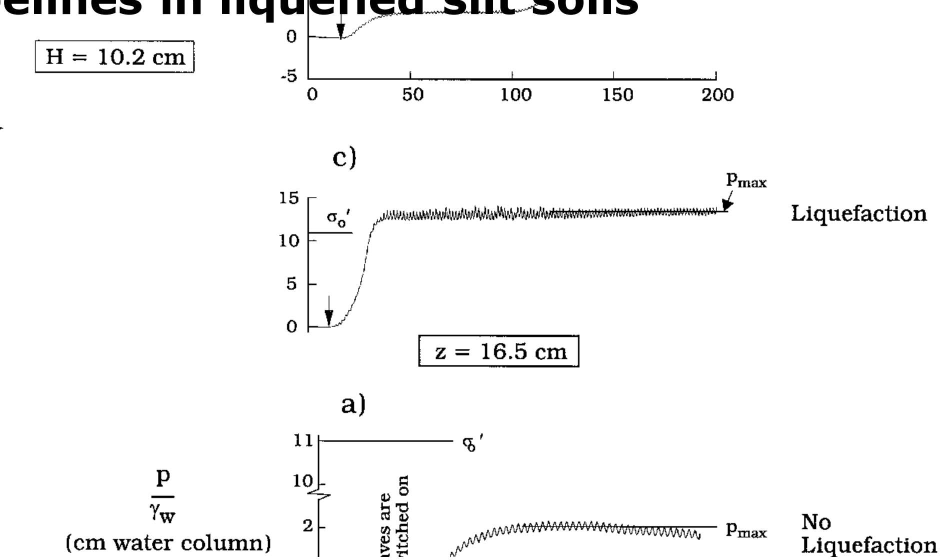
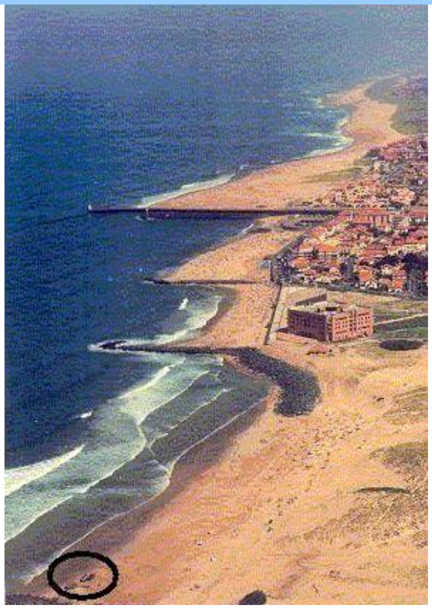




Sumer et al., Coastal Eng., 1999
Sumer et al., JWPOCE, 2006

FP5 project “Liquefaction Around Marine Structures” (LIMAS), partially funded by the European Commission



Coordination : Prof. M. Sumer
J. Waterway, Port, Coastal, and Ocean Engineering
Volume 132, N° 4, 2006
Volume 133, N° 1, 2007

Field studies of pressure transmission inside a sandy soil

Capbreton, Atlantic Ocean, France

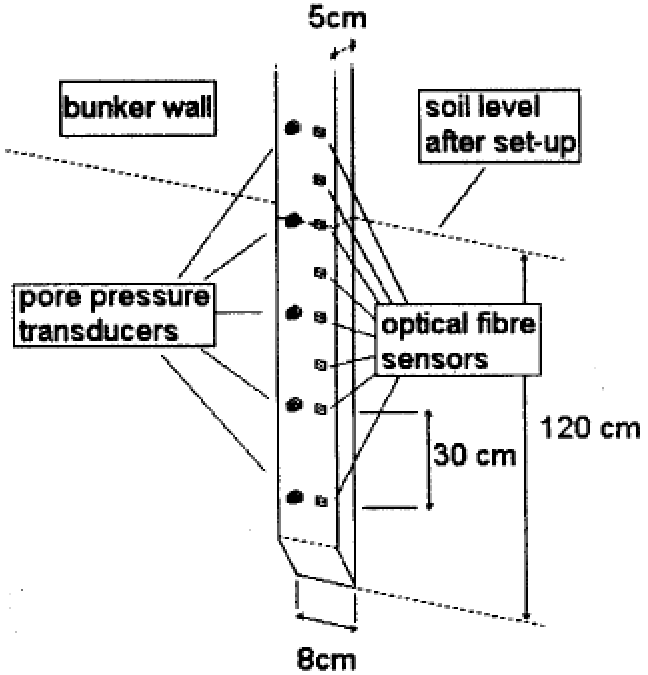
Observation of momentary liquefaction caused by waves

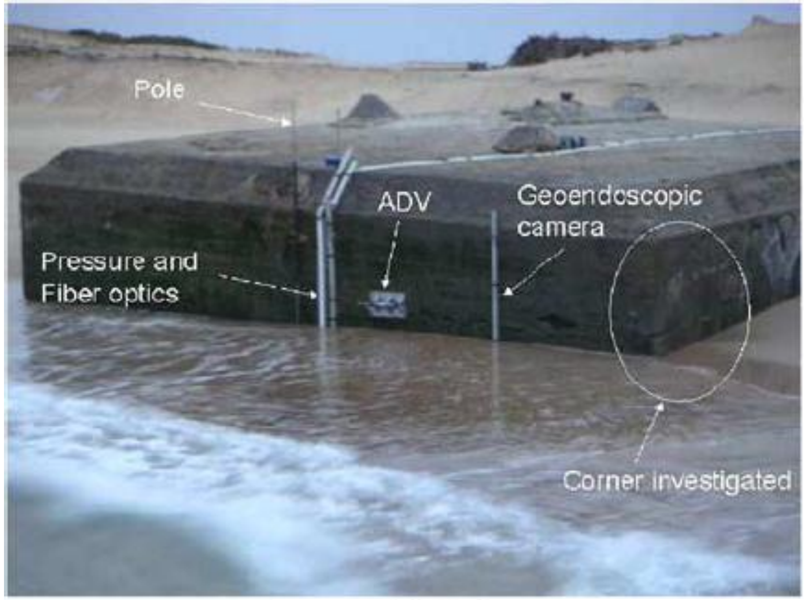
Emphasis on the effect of gas content inside the soil

Mory et al., JWPCOE, 2007
Michallet, Mory & Piedra Cueva, JGR, 2009
Breul, Hadani & Gourvès, Can. Geotech J.,2008

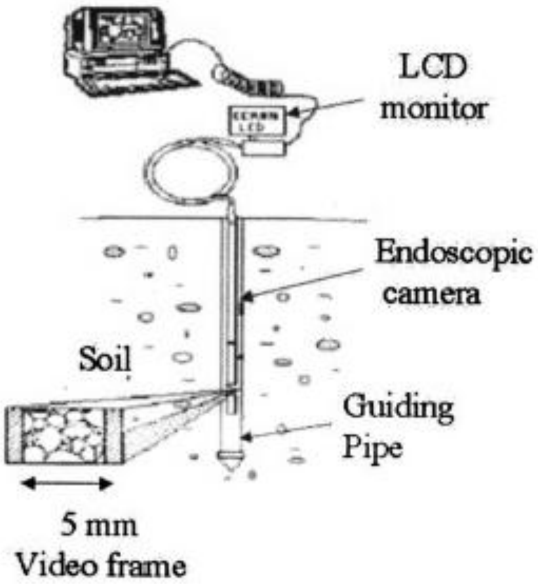
Instrumentation

Pressure measurements inside the soil and determination of the bed level



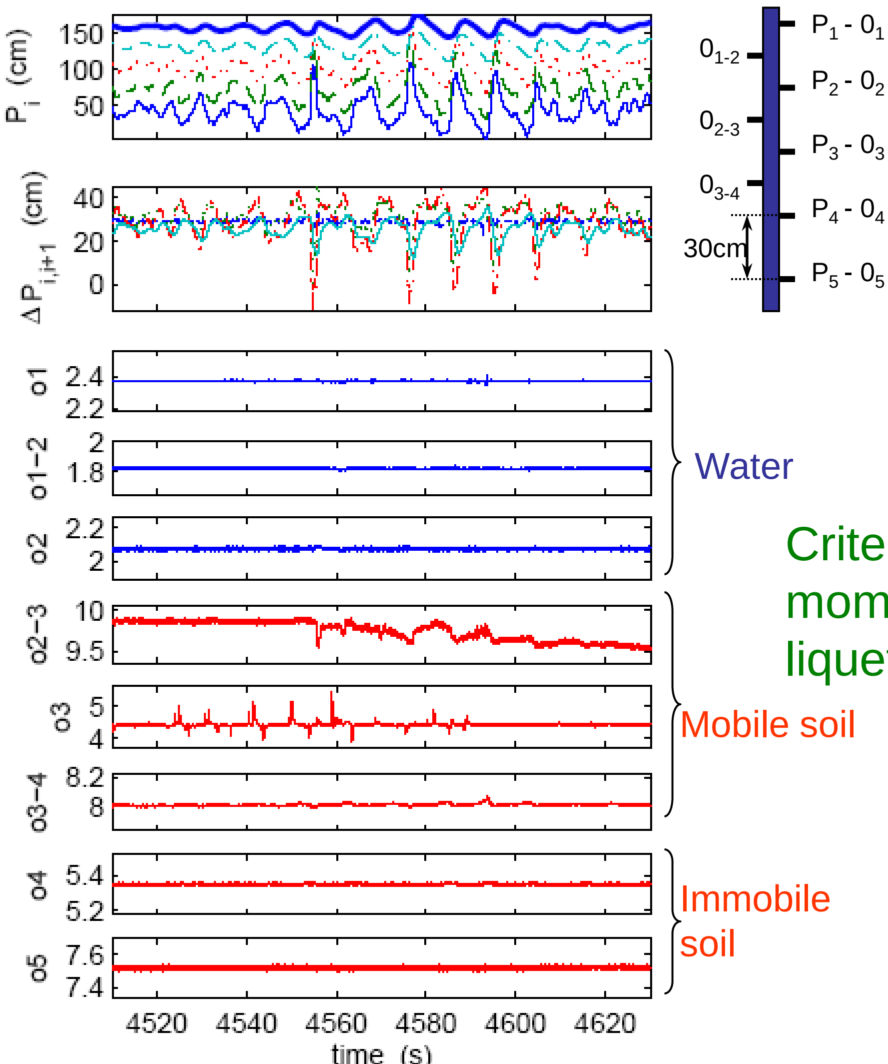


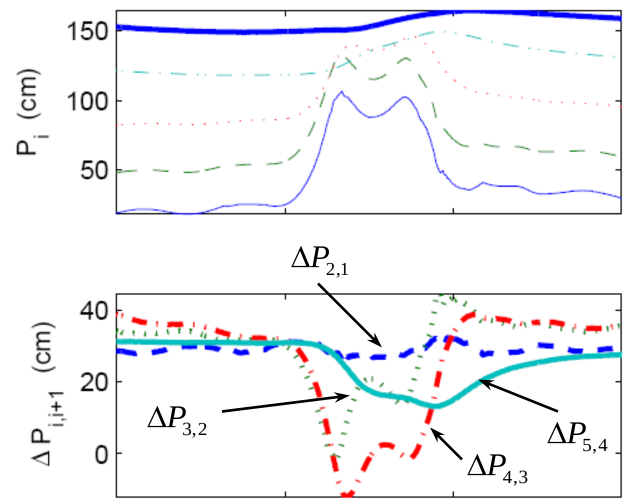
Geoendoscopic camera system for gas content observation



LERMES, Clermont-Ferrand, France

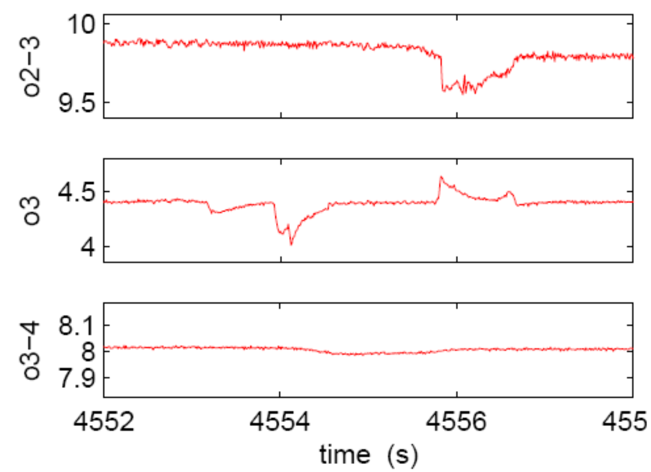
Decay of pore pressure variations inside the sandy soil





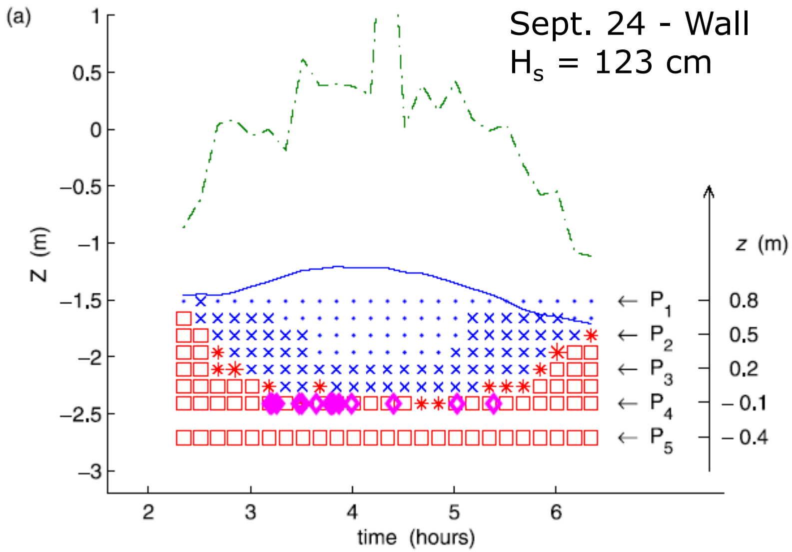
Criterion for momentary liquefaction

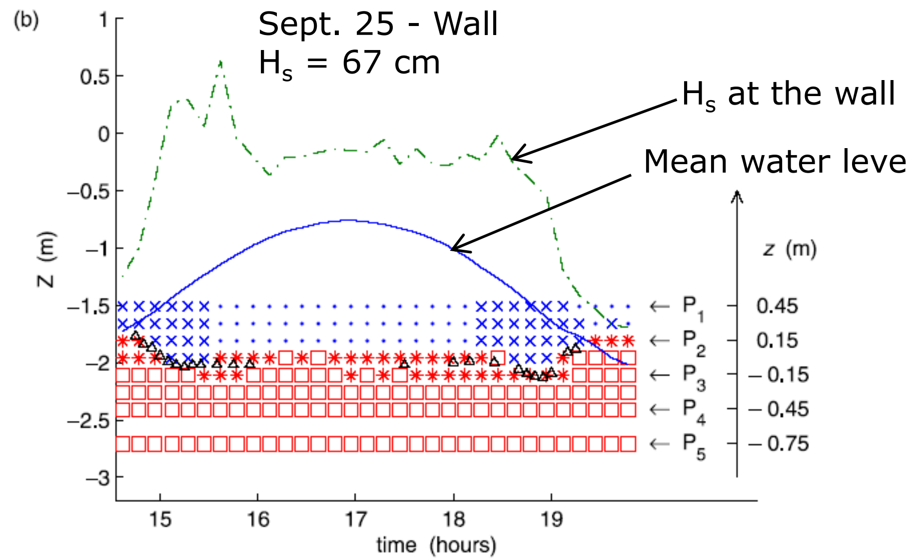
$$\frac{\Delta P_{i,i-1}}{\rho_{water}\, g} = \frac{P_i - P_{i-1}}{\rho_{water}\, g} > h\left[\frac{\rho_{sed}}{\rho_{water}}(1-\epsilon)+\epsilon\right]$$



Sept. 25, 2003
t=15h48

Bed changes during a tidal period and liquefaction events

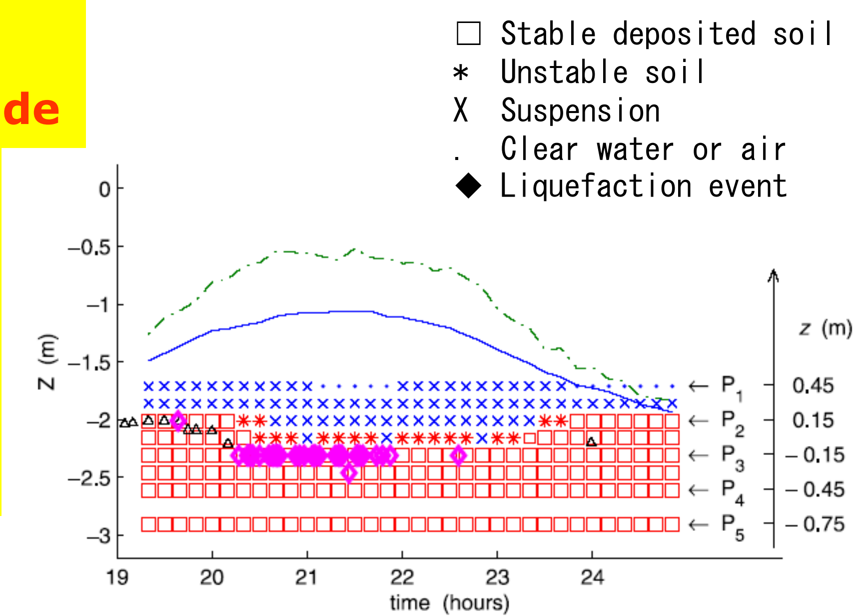




Erosion is produced during rising tide.
Sand is re-deposited at the end of the tide

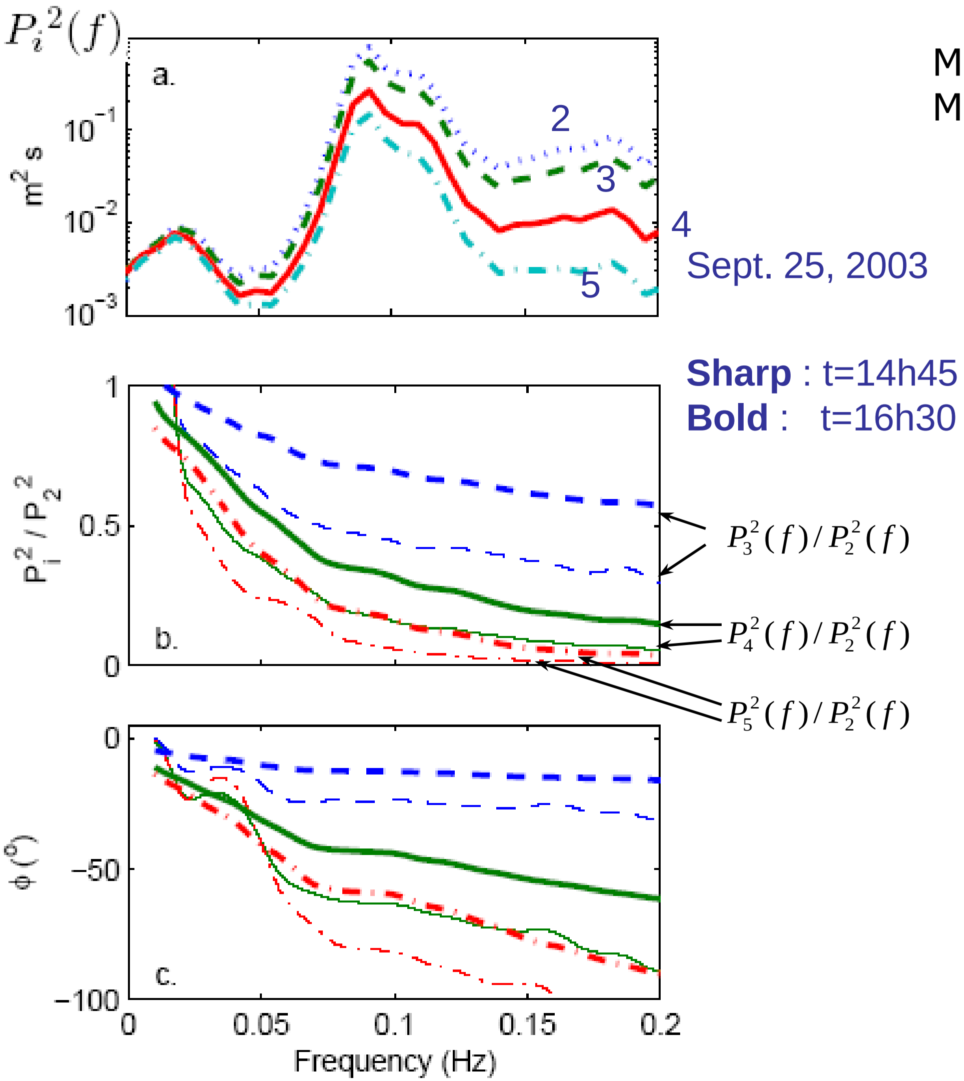
Occurrence of momentary liquefaction events :

- mainly during the initial stage of the tidal period
- requires a minimum wave height level



Oct. 1 - Corner
H_s = 69 cm

Analysis of the transmission inside the soil of pressure variations by Fourier frequency series



Mory et al., 2007
Michallet, Mory & Piedra Cueva, 2009

Change in soil properties during a tidal period

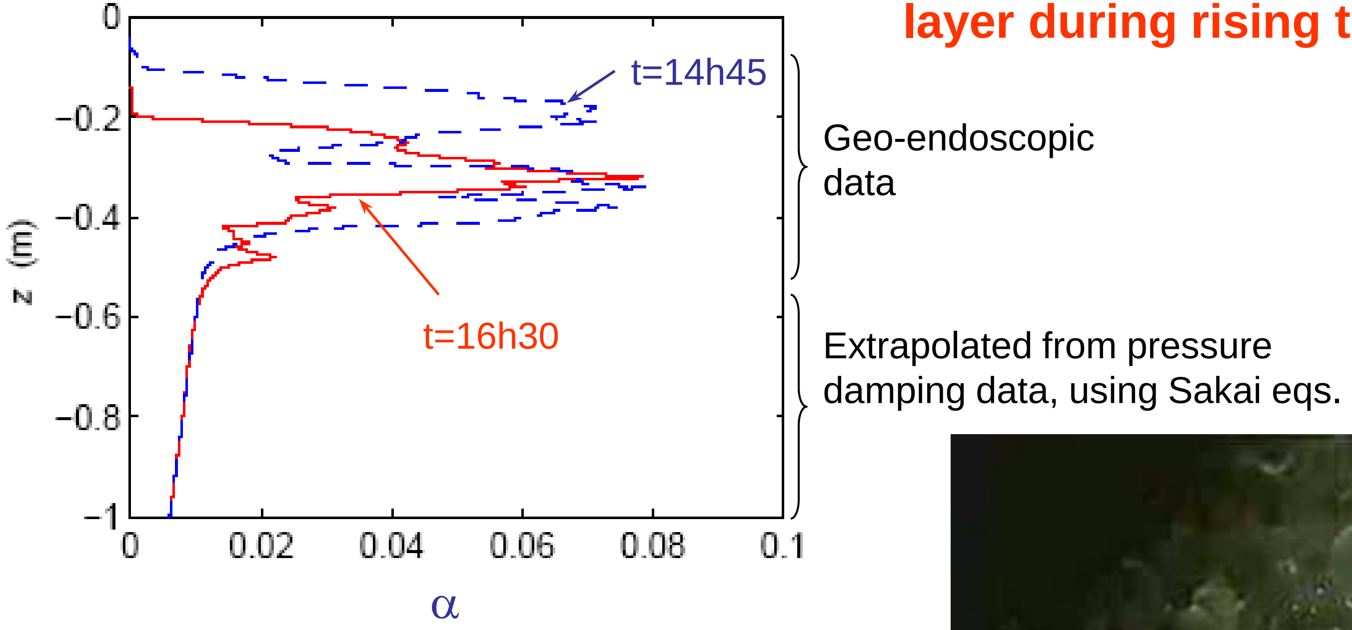
Damping of pore pressure variations inside the soil is weaker at the end of tidal period than during rising tide

Effect also seen on phase shifts

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

(Breul, Hadani & Gourvès, Can. Geotechn. J., 2008)

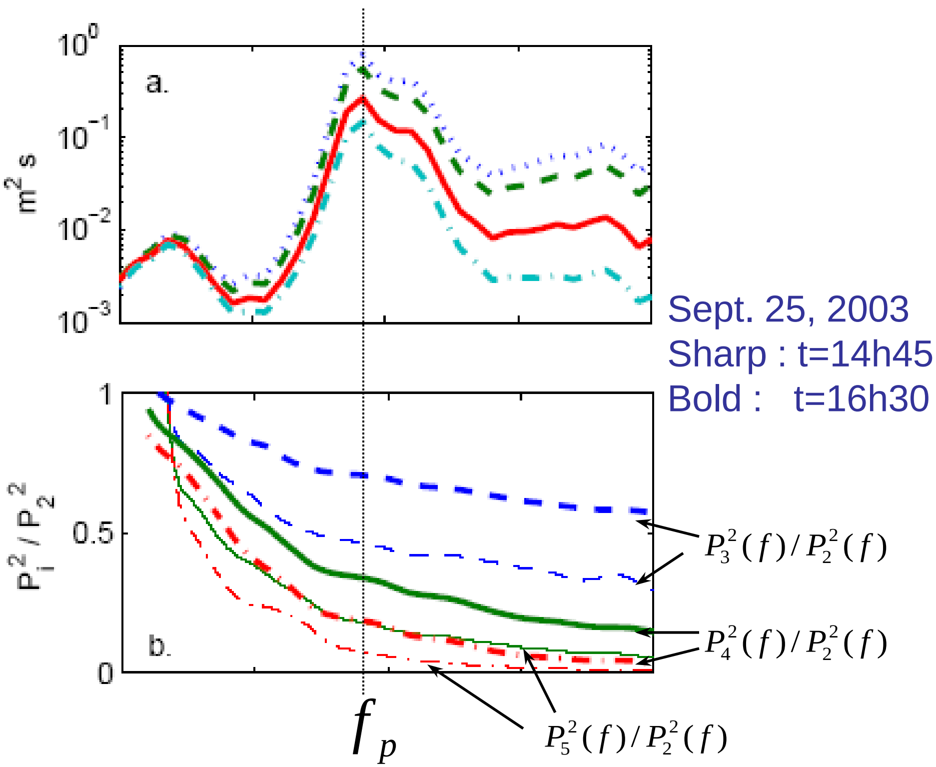
Gas escapes from the upper soil layer during rising tide



Sept. 25, 2003

P. Breul, LERMES

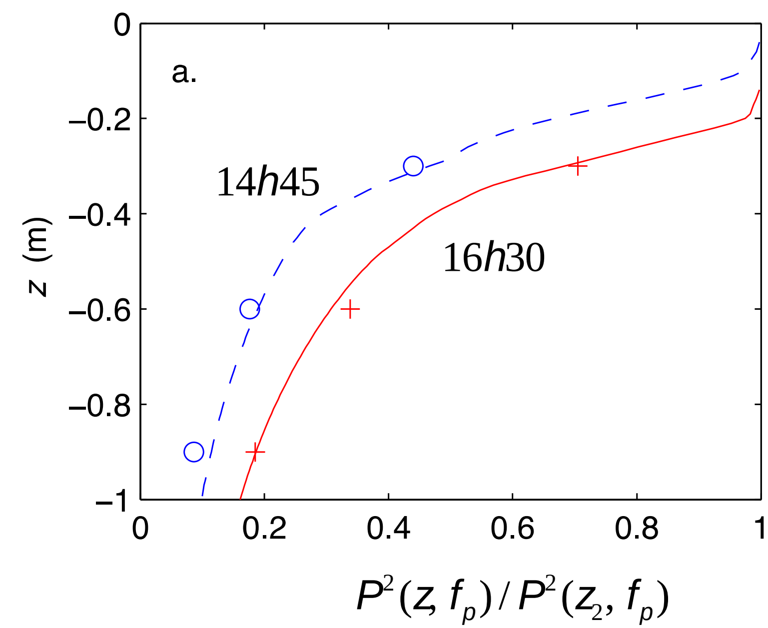
Comparison of the measured damping of pore pressure variations in the soil with the prediction by Sakai eqs. using the measured profiles of air contained in the soil



Loose sand : ε=0.5,

G=2 10^7 Pa, ν=0.498,

k=2 10^{-11} m^2



Sakai, Hatanaka & Mase, 1992

$$\frac{P_i^2(f)}{P_{i-1}^2(f)} = \exp\{-2(z_i - z_{i-1})/d\}$$

$$d = \left(\frac{Gk}{\mu\pi f_p}\right)^{1/2} \left(\varepsilon G c + \frac{1-2\nu}{2(1-\nu)}\right)^{1/2} \approx \left(\frac{P_{ref} k}{\mu\pi f_p \alpha\varepsilon}\right)^{1/2}$$

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

Comparison of the measured damping of pore pressure variations in the soil with the prediction by Sakai eqs. for constant gas content along the vertical

Synthesis of 13 tidal cycles over 9 days:

Significant wave height range : 0.19 m < H_s < 1.23 m.

2 positions : middle of the wall or bunker corner

Loose sand parameters (solid line) :

ε=0.5,

G=2 10^7 Pa, ν=0.49,

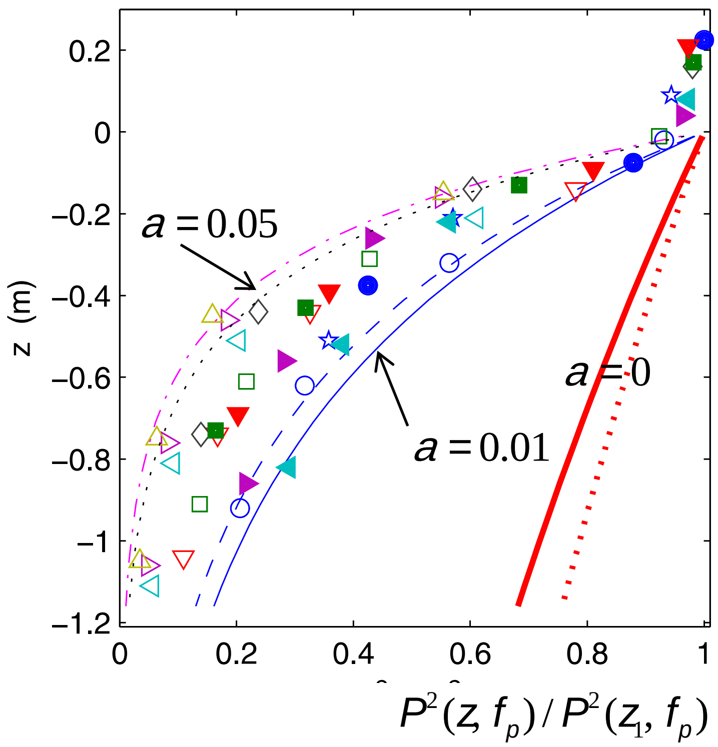
k=2 10^{-11} m^2

Compact sand parameters (dashed line) :

ε=0.4,

G=2 10^8 Pa, ν=0.33,

k=2 10^{-11} m^2



A significant amount of gas is contained inside the upper soil layers

Gas modifies the transmission of pressure variations inside the soil

Conclusions

Air content is a key parameter for quantifying the transmission of wave induced pore pressure variations inside a sandy soil

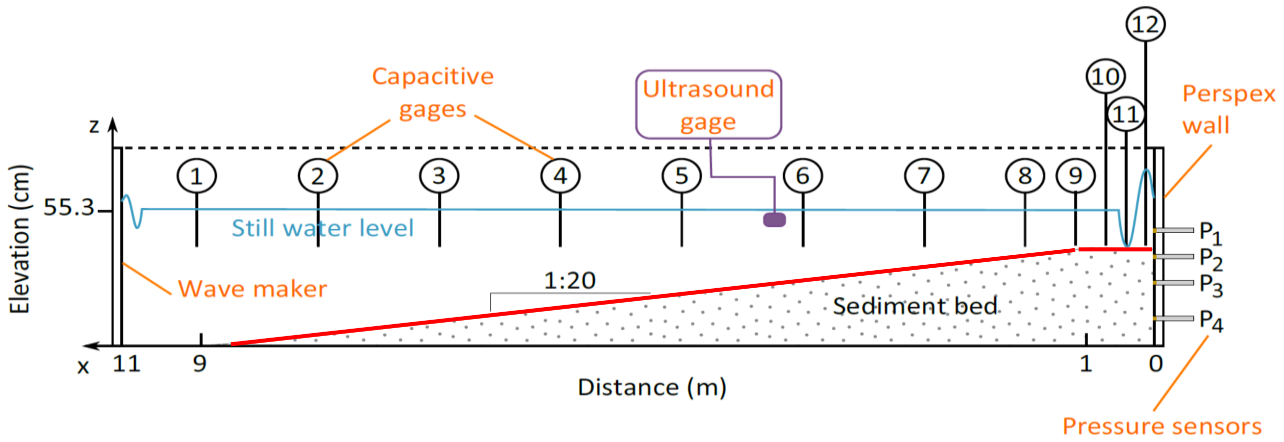
A good agreement is found between observations in the field and the prediction made using the Sakai eqs.

Air content was found at Capbreton to vary during a tidal period inside the upper soil layer

For conditions achieved in the field, the presence of gas inside the soil allows to meet conditions for which momentary liquefaction of a sandy soil occur, even for moderate wave height

In fine sediments, where liquefaction can be produced by the build up of pore pressure, the presence of air reduces the build up of pore pressure

Observations of liquefaction in the laboratory (LEGI)



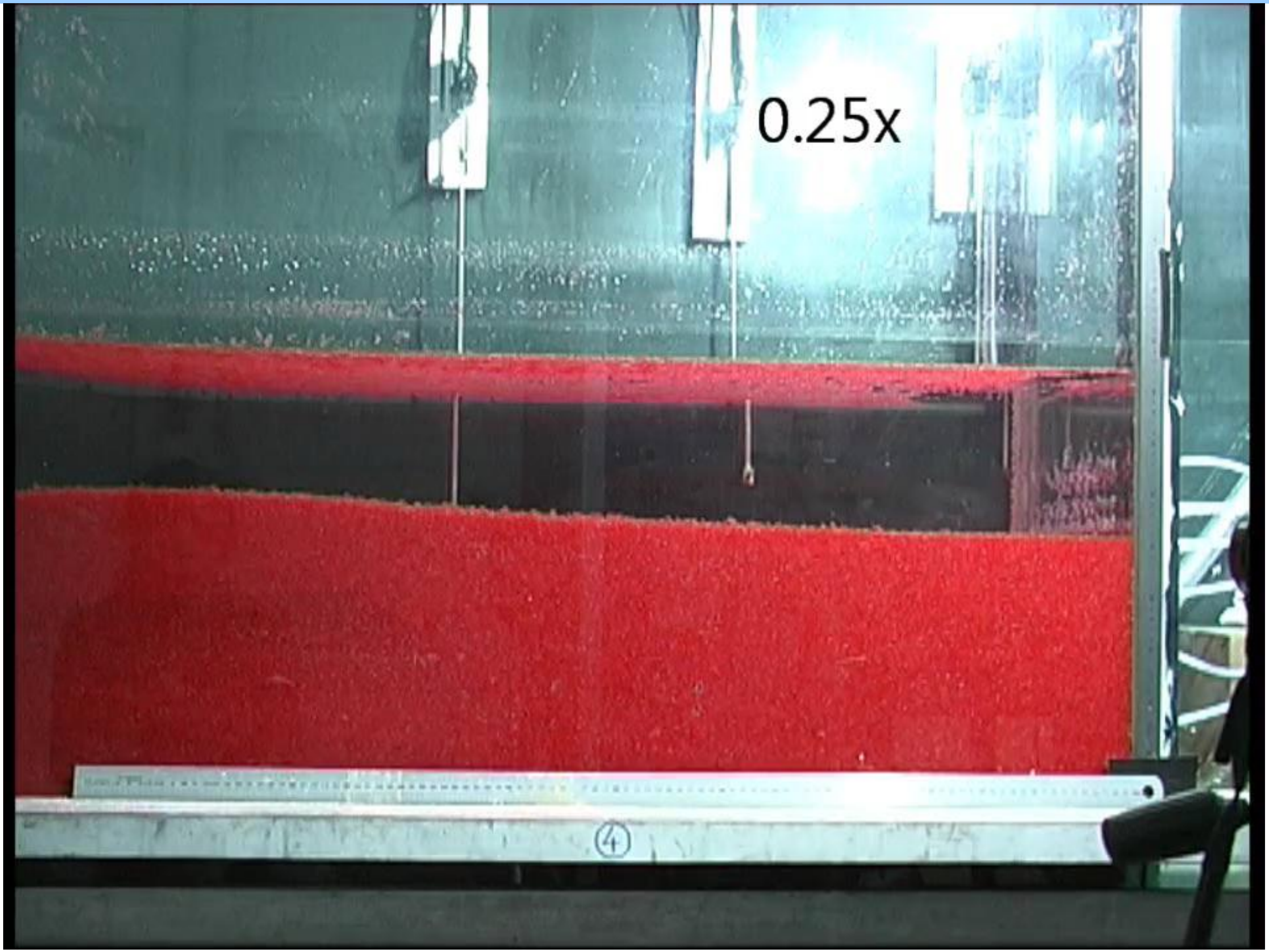
Using lightweight sediment (d_{50} = 0.64 mm, ρ_{sed}/ρ_{water} = 1.18) allows to meet the Shield and Rouse similarity between the field and the laboratory (Grasso et al., 2009)

Experiments performed in controlled conditions with un-saturated bed :

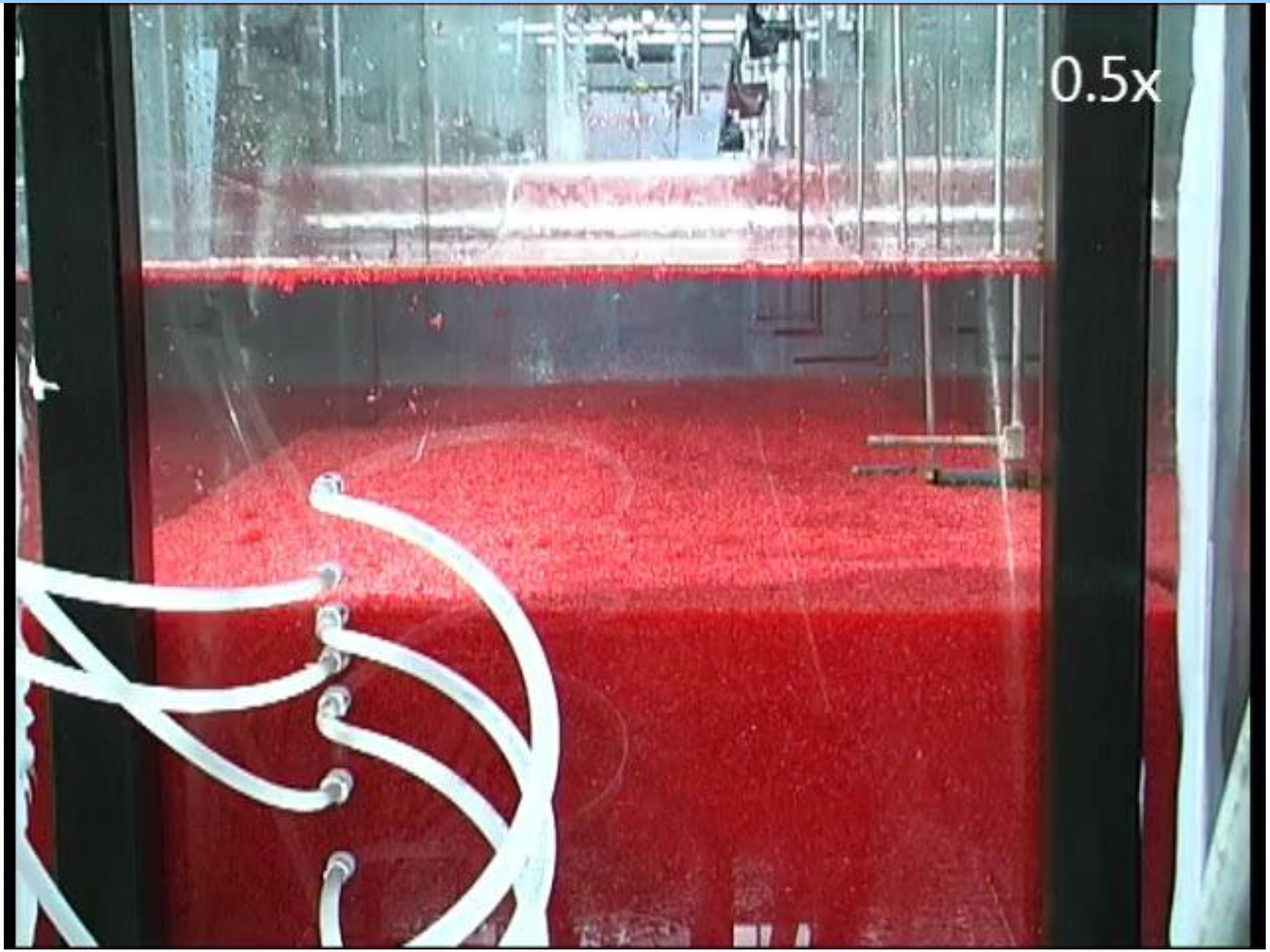
$$C_{gas} \sim 1\% \text{ to } 8\%$$

Liquefaction phenomena are promoted in the laboratory

Compact and unsaturated bed, side view

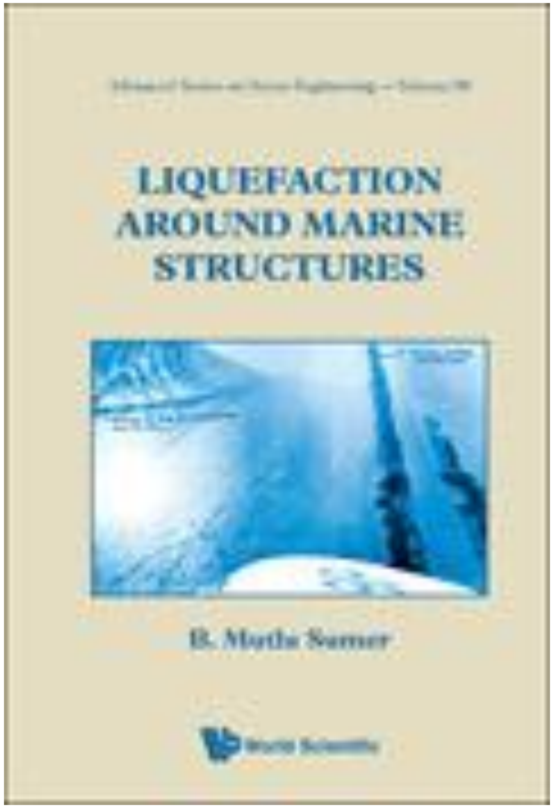


Loose and unsaturated bed, rear view



Advanced Series on Ocean Engineering:

Forthcoming Sept 2013



Mutlu SUMER
Technical University of Denmark

This book, whose primary aim is to describe liquefaction processes and their implications for marine structures such as pipelines, sea outfalls, quay walls and caisson breakwaters, discusses the subject of soil liquefaction in the marine environment.

In addition, the physics of liquefaction (including examples illustrating the catastrophic consequences of soil liquefaction with regard to marine structures) are described, and the mathematical modelling of liquefaction is treated in detail. Also, carefully selected numerical examples support the discussion of assessing liquefaction potential, and benchmark cases such as buried gas pipelines and their floatation, caisson breakwaters, cover stones and their interaction with liquefied soil along with counter measures are investigated.