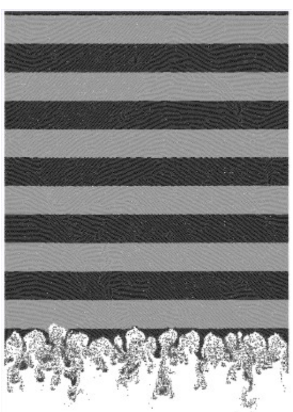
Influence du fluide intersticiel dans la liquéfaction de sédiments saturés et la lubrification des failles



- **Renaud Toussaint, Maud Schelstraete, Michael Niebling, Jean Schmittbuhl,** Institut de Physique du Globe de Strasbourg, University of Strasbourg

- **Michael Niebling, Jan Ludvig Vinningland, Øistein Johnsen, Knut-Jørgen Måløy, Eirik G. Flekkøy**, Physics Dept, University of Oslo.

- **Liran Goren, Einat Aharonov**, University of Jerusalem, **David Sparks**, Texas University, USA

Liquefaction during earthquakes:

Some famous natural cases:

- Niigata, 1964
- Izmit, 1999
- Christchurch, New Zealand, Feb 2011

Effets de liquéfaction du sol, séisme de Niigata, Ms=7,5, 16 juin 1964,Japon

Christchurch, 2011

Liquefaction during earthquakes:

Some famous natural cases:

- Niigata, 1964
- Izmit, 1999
- Christchurch, New Zealand, Feb 2011

- Typically, happens in sediments gained over the sea. The initial state is well compacted, and geoenginers expect the pore pressure to go down under dilatant shear.
- What happens? What is the role of the fluid in the liquefaction?

- Some video examples:

During the Sendai EQ, 2011, in Tokyo, in a park claimed over the sea:

2011 Japan Quake Central Park Cracks Liquefaction [www.keepvid.com].flv

Is it liquefaction? Or are these hydromechanical couplings?

Are these terms contradictory?

During Christchurch EQ:

- Backyard filling:
- Soil liquefaction Christchurch earthquake 2011 [www.keepvid.com].flv
- « Sandvolcano »:
- Sand volcano caused by liquifaction in earthquake [www.keepvid.com].flv
- Streets around:
- Christchurch Earthquake - Liquefaction as it happens [www.keepvid.com].flv

- Video demonstration of liquefaction of thixotropic sediments, Christchurch:
- Christchurch earthquake_ Watch how liquefaction occurs [www.keepvid.com].flv

Role of mechanical coupling between water and solid phase of the soil in these examples

Important role of dilatancy/contractance of the saturated sediments. The water does not need to be present at the surface, to get underground liquefaction of sediments

- Niigata 1964, airplane view:
- Best example of earthquake-induced liquefaction [www.keepvid.com].flv

- Related phenomena: Quicksand

Mont St Michel, dilatancy and hydromechanical coupling:

How to Get out of Quicksand [www.keepvid.com].flv

Viscoelastic behavior: elasticity felt at high speed:

Walking on quicksand on Morecambe Bay [www.keepvid.com].flv

- Is water (and hydromechanical coupling) needed for liquefaction?

Tabletop shaking experiments:

Dry case, granular flow under shaking:

Liquefaction [www.keepvid.com].flv

No significant penetration of the top structure (Brasilian nut effect: big objects float)

Wet case:

Sand Liquefaction Video [www.keepvid.com](2).flv

- Natural cases in quicksands: wet ones (most common):

- Lake Michigan Quicksand [www.keepvid.com].flv
- Sinking sand [www.keepvid.com].flv
- Dry ones – fracture of a porous large cohesive crust (as studied by Dirk Kadau and Hans Herrmann):
- Quick Sand [www.keepvid.com](2).flv

- Phenomenon happening during EQ in sediments and saturated soils,
- Mudflow in free slope instabilities,
- (laves torentielles, idem MontFaucon)

holy shit mud slide frazier slide [www.keepvid.com].flv

- Or loss of apparent friction in sheared media, as saturated fault gouges…

Quelques liens vidéos reliés à ce sujet :
For advanced fluid mechanics, on liquefaction and thixotropy,

Home made liquefaction just after the Christchurch EQ - my favourite:
http://www.youtube.com/watch?v=tvYKcCS_J7Y

Christchurch just after the EQ, last year: a backyard filling:
http://www.youtube.com/watch?v=7emGut6XmkU

streets and postman during liquefaction: http://www.youtube.com/watch?v=2pzJS15u2PA&feature=related eventually: http://www.youtube.com/watch?v=2WoKu5VxKgs&NR=1

Niigata 1964 EQ: http://www.youtube.com/watch?v=KLZFlnND0hA&feature=related

small experiment: http://www.youtube.com/watch?v=ngxG49Lf6co&feature=related this ones looks unsaturated, and obviously doesn't work so well: http://www.youtube.com/watch?v=Xow8X-bVDqM&feature=related
Sand volcano, and liquefaction during EQ:
http://www.youtube.com/watch?v=moh3jKBS_UA

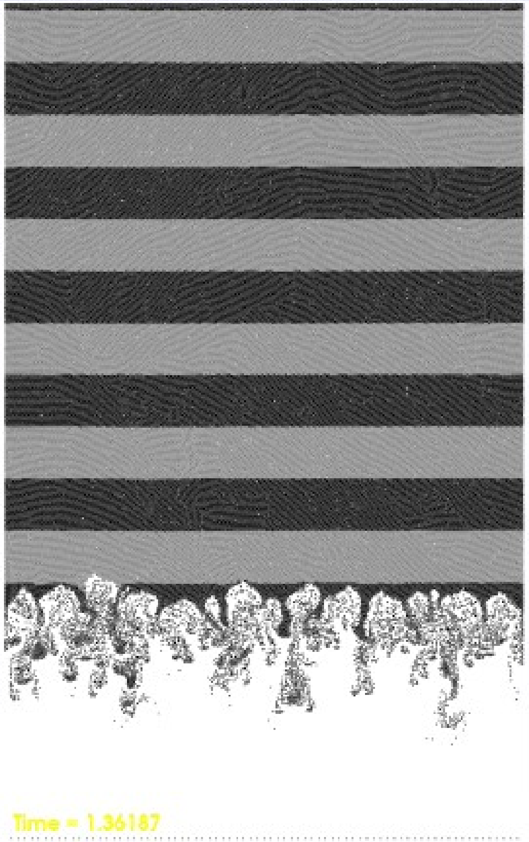
A few other funny ones, on quicksand this time: To illustrate viscoelasticity: http://www.youtube.com/watch?v=XDMD7p-b4z8 or http://www.youtube.com/watch?v=omBFjFGwRhs&feature=related practical exercises: http://www.youtube.com/watch?v=xjSYzT3CUnA&feature=related

Studied systems - the granular RT-instability

Dimensions:

- Cell-size 5 cm wide 8 cm high and 1 mm thick
- Grains: d=140 μm; $\rho_m = 2.5\, g/cm^3$ or $\rho_m = 1.05\, g/cm^3$
- Filled with an incompressible fluid $\mu_f = 0.00226$ Pas (water/glycerol) or
- Filled with a compressible fluid $\mu_f = 18.2\ 10^{-6}$ Pas (air)
- Ca. 200,000 particles in the simulations

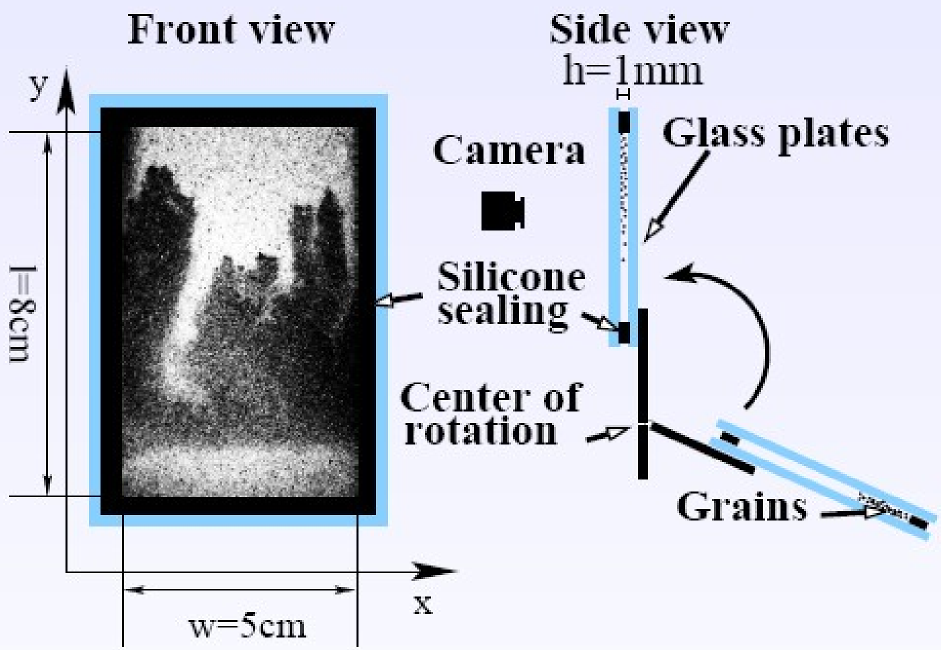
Simulations



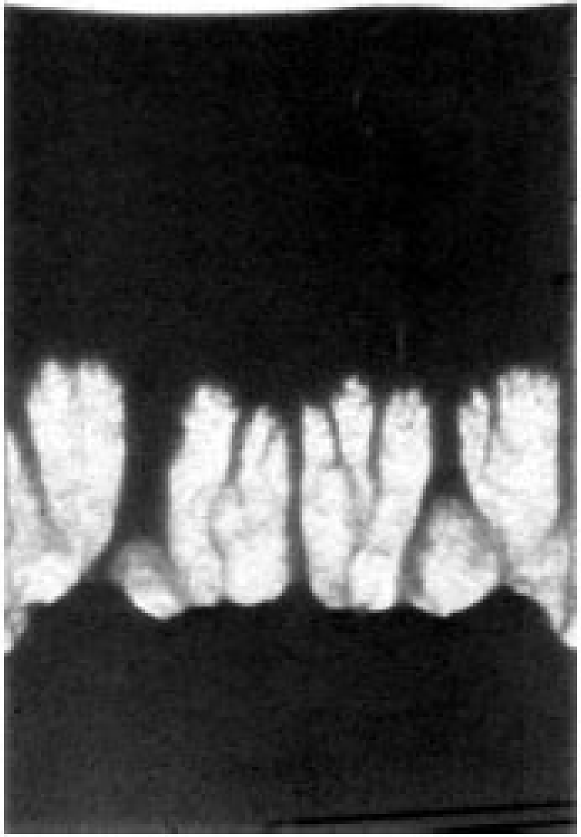
- Sedimentation problem:

Granular Rayleigh-Taylor problem

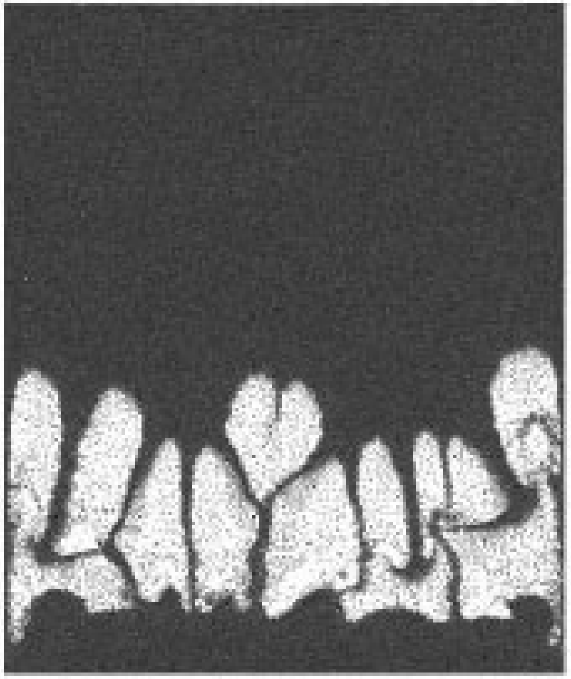
Experimental setup



- Cell filled with an incompressible fluid or a compressible fluid
- 125 fps for an incompressible fluid and 1000 fps pictures/s for a compressible fluid are taken by a high speed camera



(a) Experiment

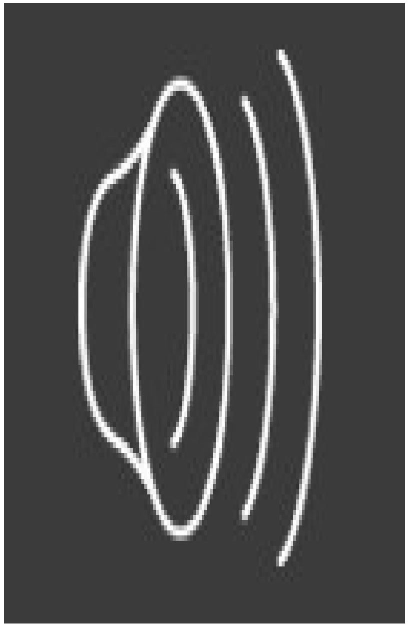


(b) Simulation

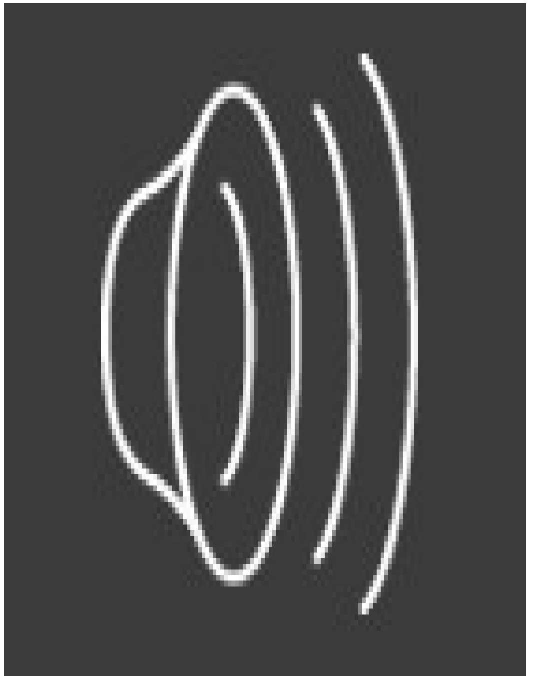
Figure 1: The left image is an experiment where a 1 mm thick, closed Hele-Shaw cell is filled with monodisperse polystyrene beads of 140 μm in diameter. The right image is a 2D simulation of the same system. The width of both systems is 56 mm, and both images are recorded 0.2 seconds after the rotation of the cell.

Sedimentation of grains in a closed air box:

- Experiments



- Simulations



Vinningland, Johnsen, Flekkoy, Toussaint, Maloy

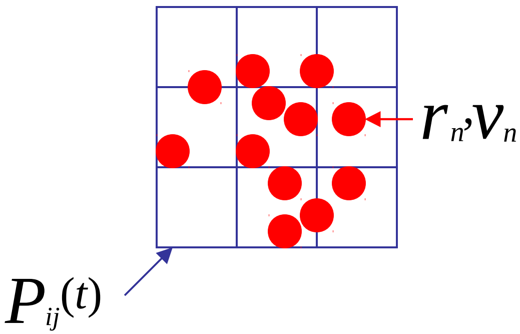
Numerical model: quasi 2D coupled granular – fluid flow.

extension of models for fluidized beds, e.g. Flekkøy and Mc Namara 2000.

Principles: coeexisting spaces:

• discrete description of the granular matrix,

• interlaced with a continuous fluid description discretized on a square lattice (2 grains diameter lattice step).



Inertia of the fluid is neglected, fluid pressure evolves according to Darcy rule and advection by the local granular matrix, plus source terms corresponding to compression/dilation rates of the granular matrix. Permeability is set by the coarse-grained porosity.

2D grains represent cylindrical stacks of grains, diameter = system's width.

Grain flow rule: Molecular dynamics,

interaction forces: central elastic repulsion proportional to overlap,

external forces: Fluid pressure gradient,

Coulomb friction from the confining plates (normal stress = weight + Janssen term proportional to in-plane stress)

Granular flow rule: momentum conservation:

$$
\begin{aligned}
ma &= F^I + F^f - \nabla P/\rho \\
F^I_{pair} &= k\delta r = KLh\frac{r_{pair}}{L} \\
F^{friction} &\leq \mu_s \sigma_n L^2 = \mu_s[\rho_g g h + k_{janssen}\sigma_{||}]L^2
\end{aligned}
$$

where:

$$
\begin{aligned}
m = \rho_g L^2 h &: \text{particle mass} \\
K &: \text{glass Young modulus} \\
\rho &: \text{number density} \\
L &: \text{particle diam} \\
\rho_g &: \text{glass bulk mass density} \\
h &: \text{cell width} \\
\mu_s &: \text{Coulomb friction parameter} \\
g &: \text{gravitational acceleration} \\
k : \text{spring constant};\ r_{pair} &: \text{particle separation}
\end{aligned}
$$

$\boxed{\text{Dynamic equation for the fluid flow:}}$

$$
\begin{aligned}
\text{volume conservation of grains} & & \\
\partial_t \rho_s + \nabla \cdot (\rho_s u) &= 0 \\
\text{mass conservation of gas-Darcy} & & \\
\partial_t \rho_a + \nabla \cdot [\rho_a (u - \frac{\kappa(\rho_s)}{\mu \phi} \nabla P)] &= 0 \\
\text{state equation of air} & & (\phi = 1 - \rho_s) \\
\rho_a & \alpha \quad \phi P \\
\text{Carman - Kozeny} & & \\
\kappa(\phi) &= \frac{L^2}{45} \frac{\phi^3}{(1-\phi)^2}
\end{aligned}
$$

leads to

$$
\boxed{\phi[\partial_t P + u \cdot \nabla P] = \nabla \cdot [P \frac{\kappa}{\mu} \nabla P] - P \nabla \cdot u}
$$

Lubrication and liquefaction of a sheared saturated layer

coupled fluid-solid deformation of fluid-filled granular media, under different boundary, drainage conditions, and forcing scenario.

- $Whataretheprocessescontrollingporepressureevolution\star$
- $Whataretheimportantparameters\star$
- $Whenshouldweexpecttoseehardening\star$
- $Howdoesfrictiondependondrainageconditions\star$

Goren, L., E. Aharonov, D. Sparks and R. Toussaint; ``Pore pressure evolution in deforming granular material: A general formulation and the infinitely stiff approximation, J. Geophys. Res., 115, B09216, (2010). doi:10.1029/2009JB007191

Goren, L., E. Aharonov, D. Sparks and R. Toussaint; ``The mechanical coupling of fluid-filled granular material under shear'', P.A.Geoph., 2011.

Part 1: Formulation for the physics of pore fluid

Wang, 2000, Biot, 1956 (when neglecting inertia), Bechrach et al., 2001 (when neglecting inertia), Walder & Nur, 1984, Snieder & van der Beukel, 2004, Samuelson et al., 2009

Grains mass conservation :

$$\frac{\partial\left[(1-\phi)\rho_s\right]}{\partial t}+\nabla\cdot\left[(1-\phi)\rho_s\vec{u}_s\right]=0$$

Fluid mass conservation :

$$\frac{\partial\left[\phi\rho_f\right]}{\partial t}+\nabla\cdot\left[\phi\rho_f\vec{u}_f\right]=0$$

Darcy :

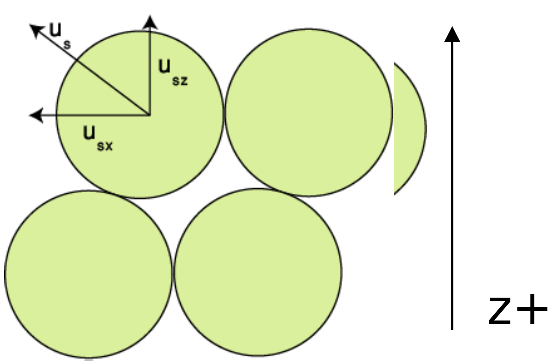
$$\vec{u}_f-\vec{u}_s=-\frac{k}{\mu\phi}\nabla P$$

Fluid state :

$$\rho_f=\rho_0\left(1+\beta P\right)$$

Fluid compressibility

$$\frac{\partial P}{\partial t}=\underbrace{\frac{1}{\beta\Phi}\nabla\cdot\left[\frac{k}{\mu}\nabla p\right]}_{Diffusion}-\underbrace{\frac{\partial\Phi/\partial t}{\beta\Phi(1-\Phi)}}_{Forcing}$$



Two regimes for the evolution of pore pressure

Undrained boundary conditions

$$\frac{\partial P}{\partial t} = \frac{1}{\beta\Phi}\cancel{\nabla\cdot\left[\frac{k}{\mu}\nabla p\right]} - \frac{\partial\Phi/\partial t}{\beta\Phi(1-\Phi)}$$

$$\Delta P = -\frac{1}{\beta}\frac{\Delta\Phi}{\Phi(1-\Phi)}$$

PorePressureevolution dependsontheoverallstrain ofporosity

***Elastic-like**behavior*

Drained Boundary conditions

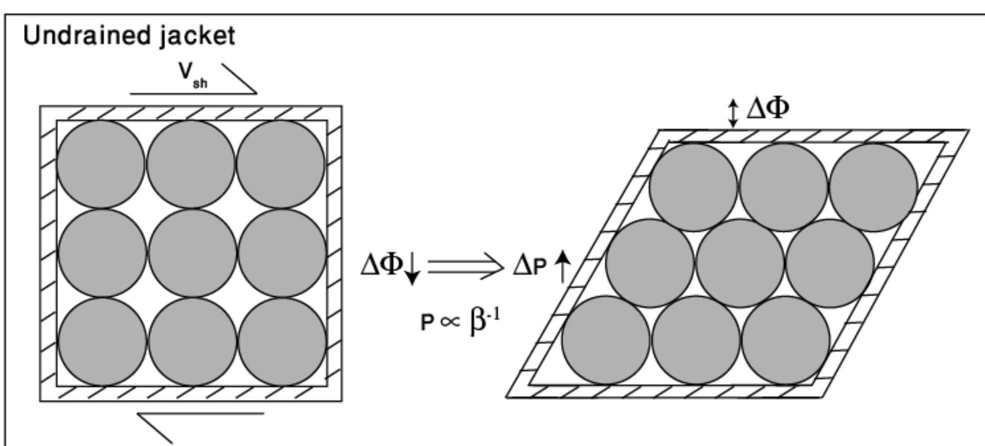
$$\cancel{\frac{\partial P}{\partial t}} = \frac{1}{\beta\Phi}\nabla\cdot\left[\frac{k}{\mu}\nabla p\right] - \frac{\partial\Phi/\partial t}{\beta\Phi(1-\Phi)}$$

$$P(t) \propto -\eta\frac{\partial\Phi(t)}{\partial t}$$

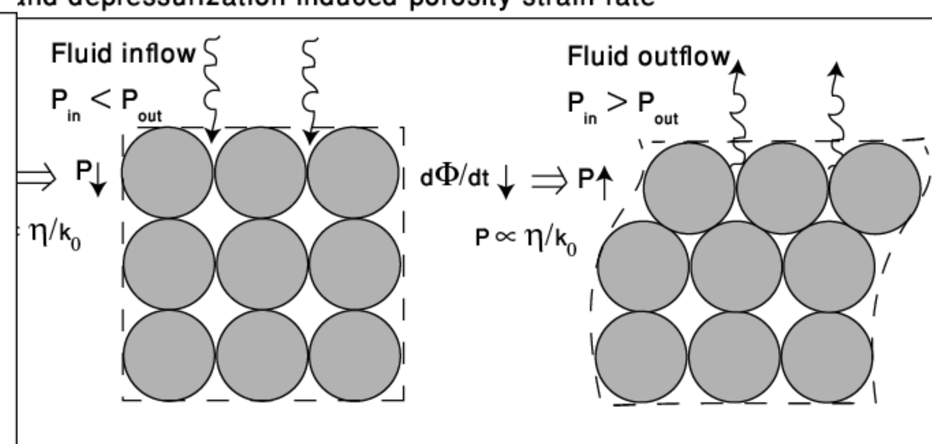
PorePressureevolution dependsonthestrain-rateof porosity

***Viscous-like**behavior*

Elastic pressurization and depressurization induced by porosity strain

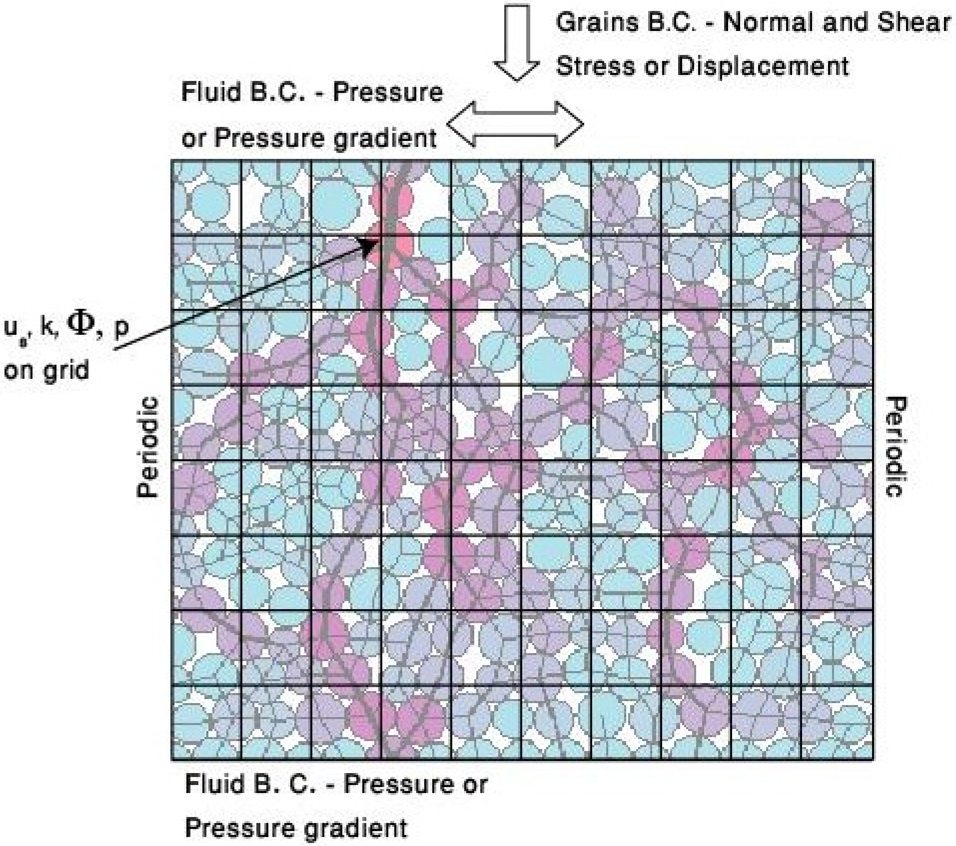


and depressurization induced porosity strain rate



2-phase 2-scale model

(McNamara et al. 2000)



Soliddeformation changesthefluidpressure viathetemporalderivative ofporosity $d\Phi/dt$

andthechangeofporosity

$$\Delta\Phi$$

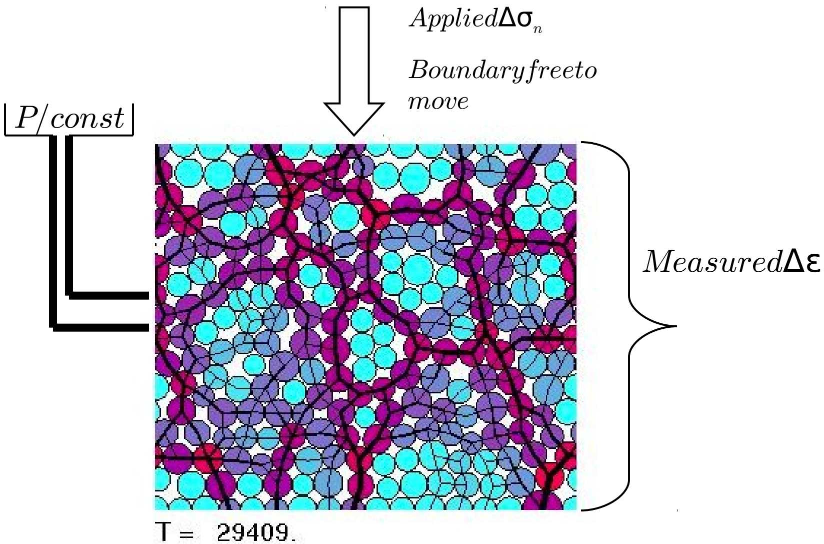
Fluidpressure gradients ∇P

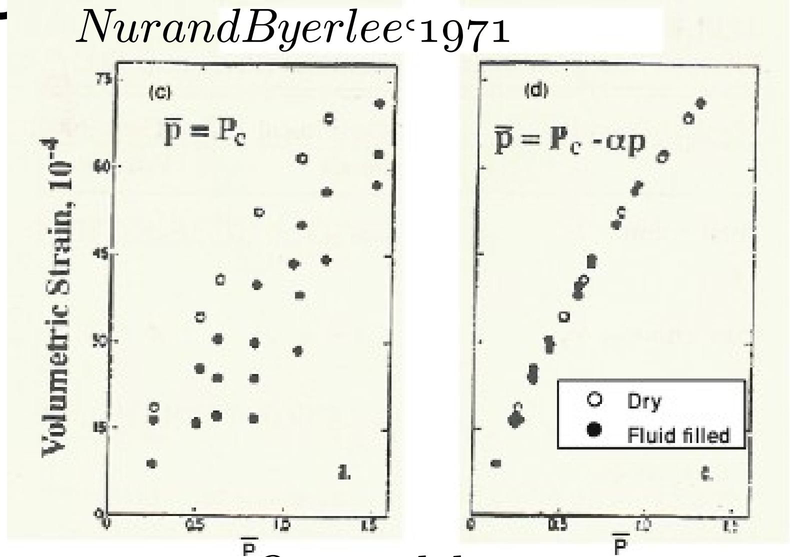
actasaforceaffecting thesolidgrainmotion▷

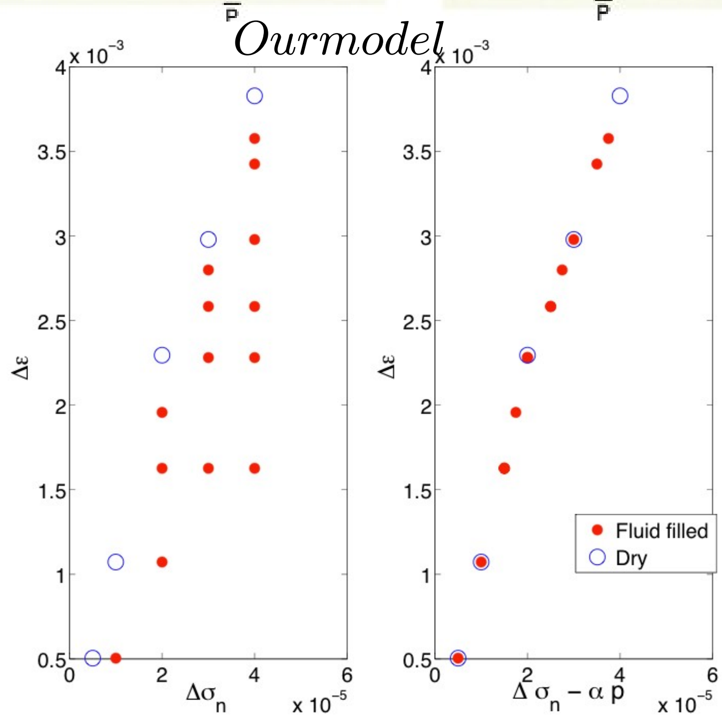
Linear momentum forgraini.

$$m_i v_i = \sum_j F_{ij} - \frac{\nabla P \cdot V_i}{1-\Phi}$$

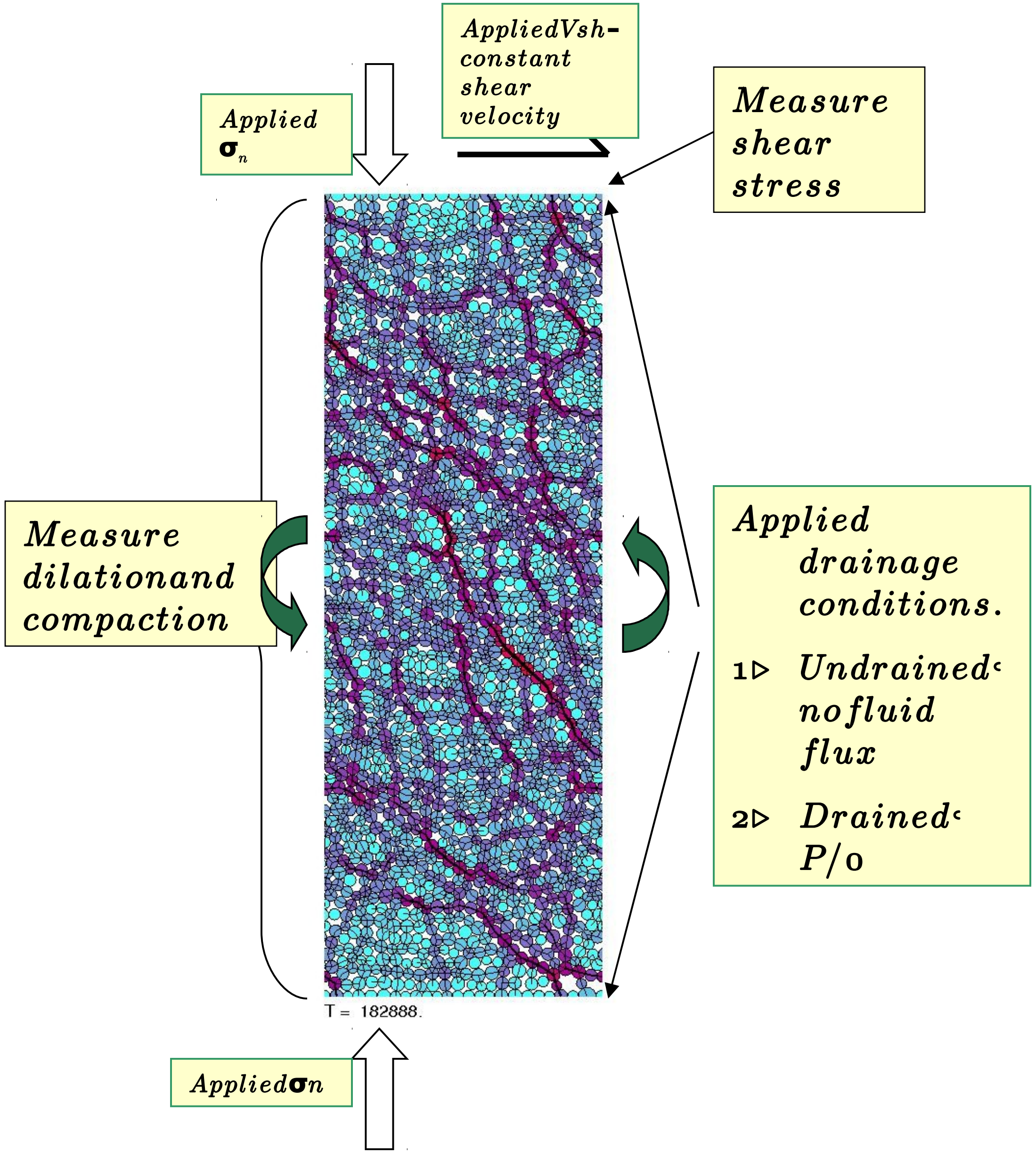
Validation by simulating the effective stress law

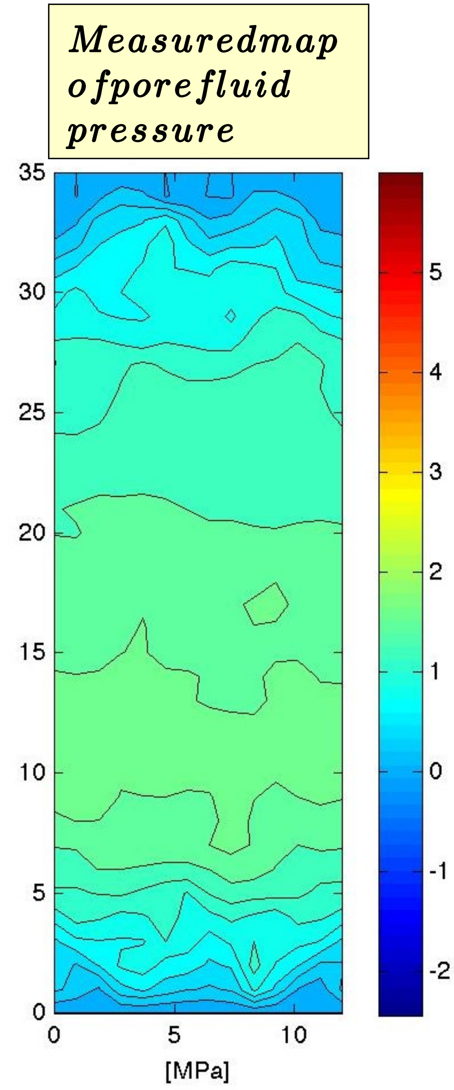






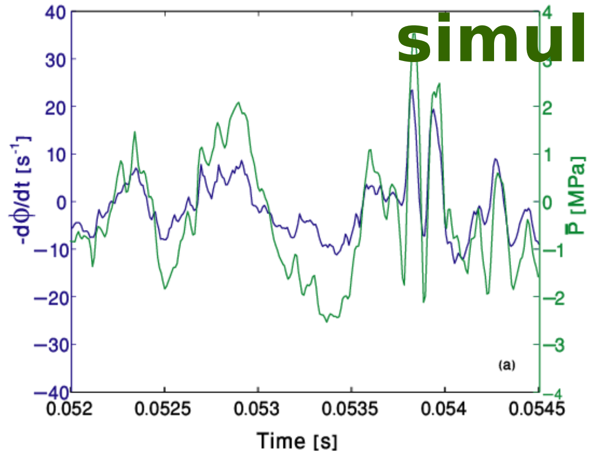
Shear at constant velocity

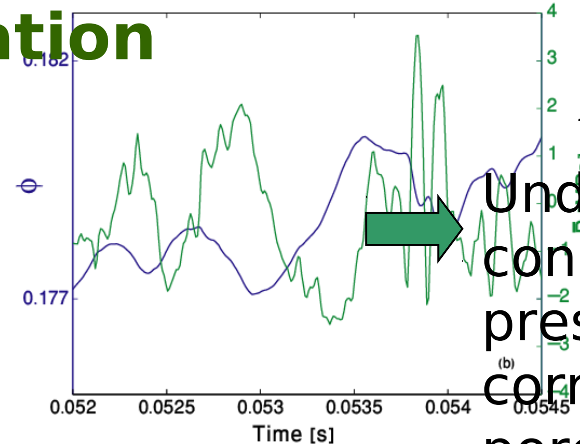




What controls the pore pressure in the fully coupled model?

Drained simulation

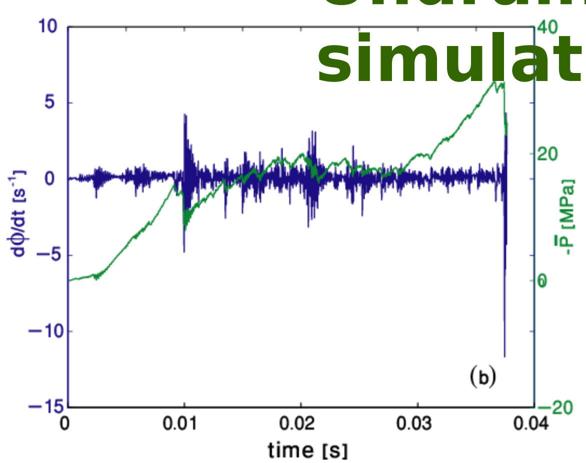


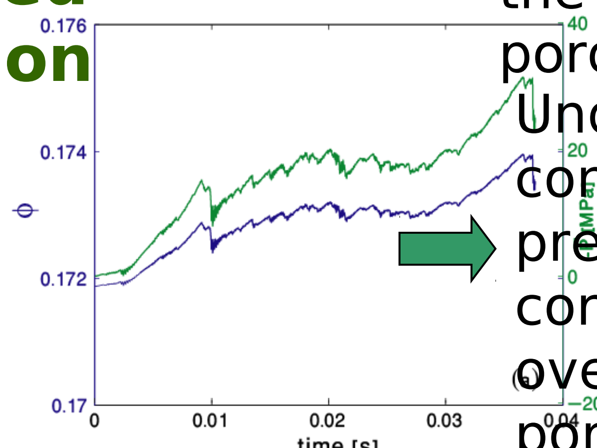


$$p \propto \partial\Phi / \partial t$$

Under drained conditions pore pressure is correlated with pores strain rate and is not correlated with the overall change of porosity

Undrained simulation



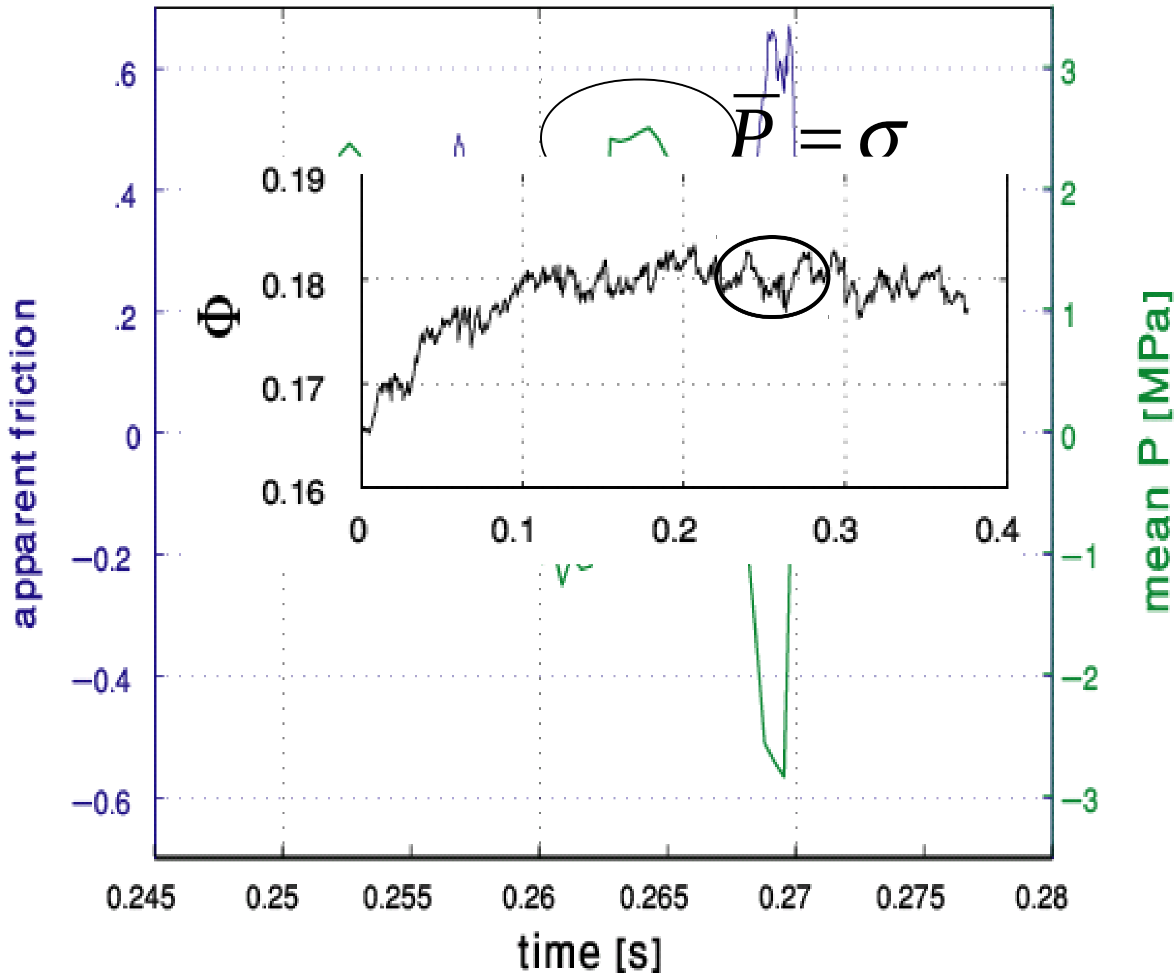


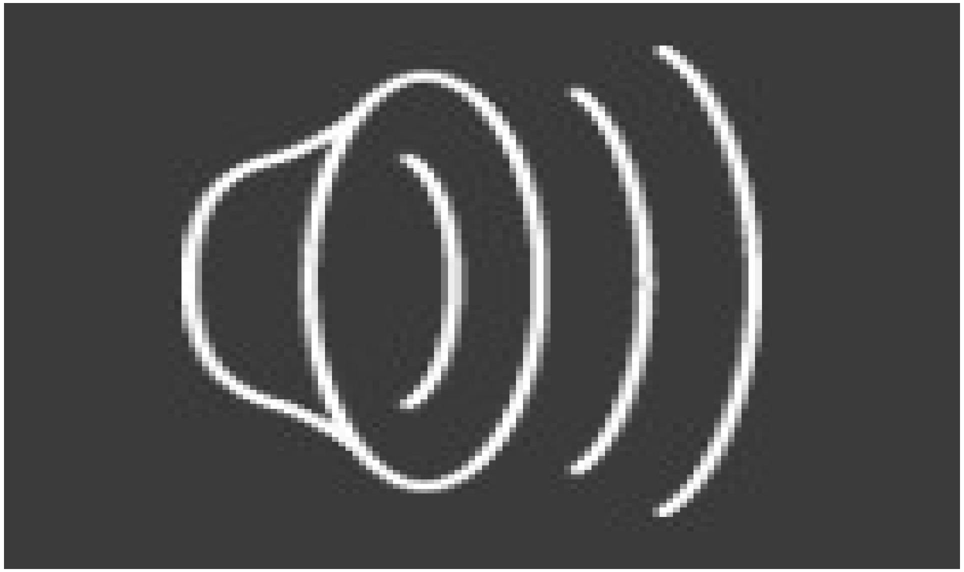
$$\Delta p \propto \Delta\Phi$$

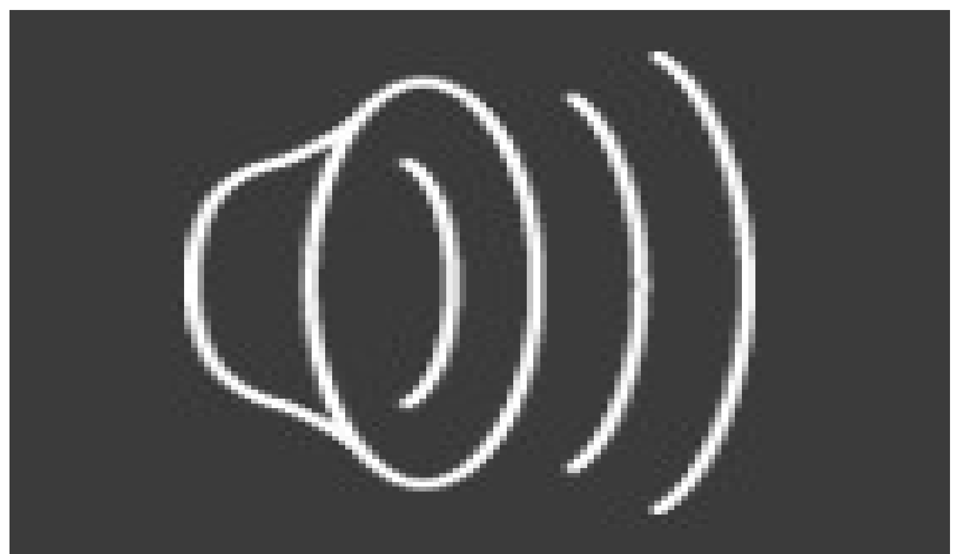
Under undrained conditions, pore pressure is correlated with overall volumetric pore strain and is

Liquefaction events under drained conditions

Vsh = 0.76 m/s and σn = 2.4 MPa (100 m)





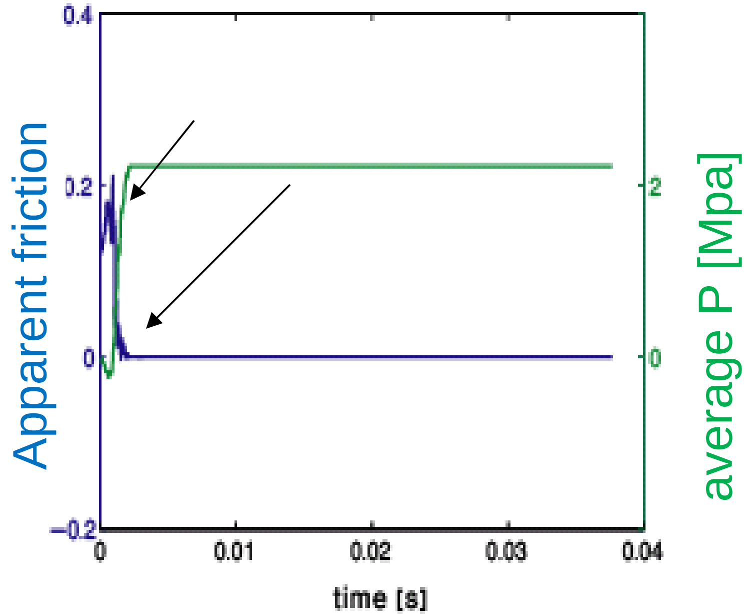


Dynamic lubrication event.
Origin: spatiotemporal localization of the elastic energy by the force arches, transfer of the pressure to the nearby fluid

solid stress and fluid pressure in the shear zone

Liquefaction and hardening under undrained conditions:
Vsh = 0.76 m/s and σn = 2.4 MPa (100 m

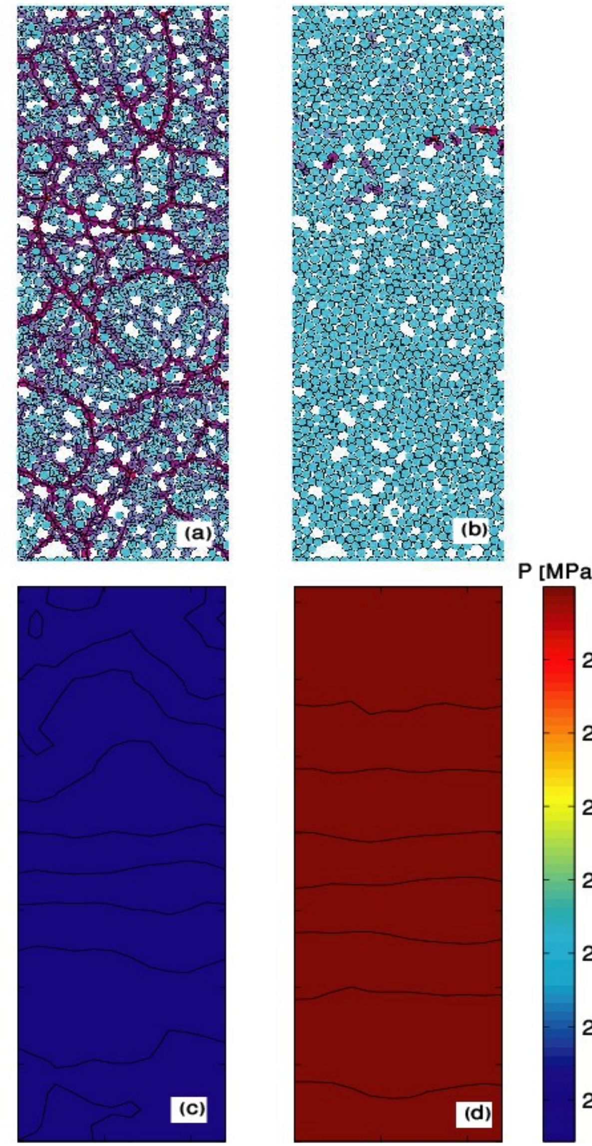
Initial loose



Dilatancy hardening

Steady state liquefaction

$$\Delta\Phi \updownarrow \Rightarrow \Delta P \updownarrow \Rightarrow \mu_a \updownarrow$$



Nombre de Deborah

- Rapport forces visqueuses / forces elastiques,
- tps de diffusion de pression/ tps caractéristique de déformation:

l: epaisseur

U: vitesse

D: diffusivité de pression

$$\mathrm{De} = \frac{l u_0}{D} = \frac{l u_0 \beta \eta \Phi}{k_0}.$$

De >>1 : undrained

De << 1: well drained

$$\frac{\partial \hat{P}}{\partial \hat{t}} - \mathrm{De}^{-1} \hat{\nabla} \cdot (\hat{k} \hat{\nabla} \hat{P}) + \frac{1}{\Phi} \hat{\nabla} \cdot \hat{\mathbf{u}}_{\mathrm{s}} = 0,$$

Evaluating a liquefaction potential

- If LP>1, lubrication events (where transiently)

and possible liquefaction:

$\lambda = 0.01$

ζ layer thickness

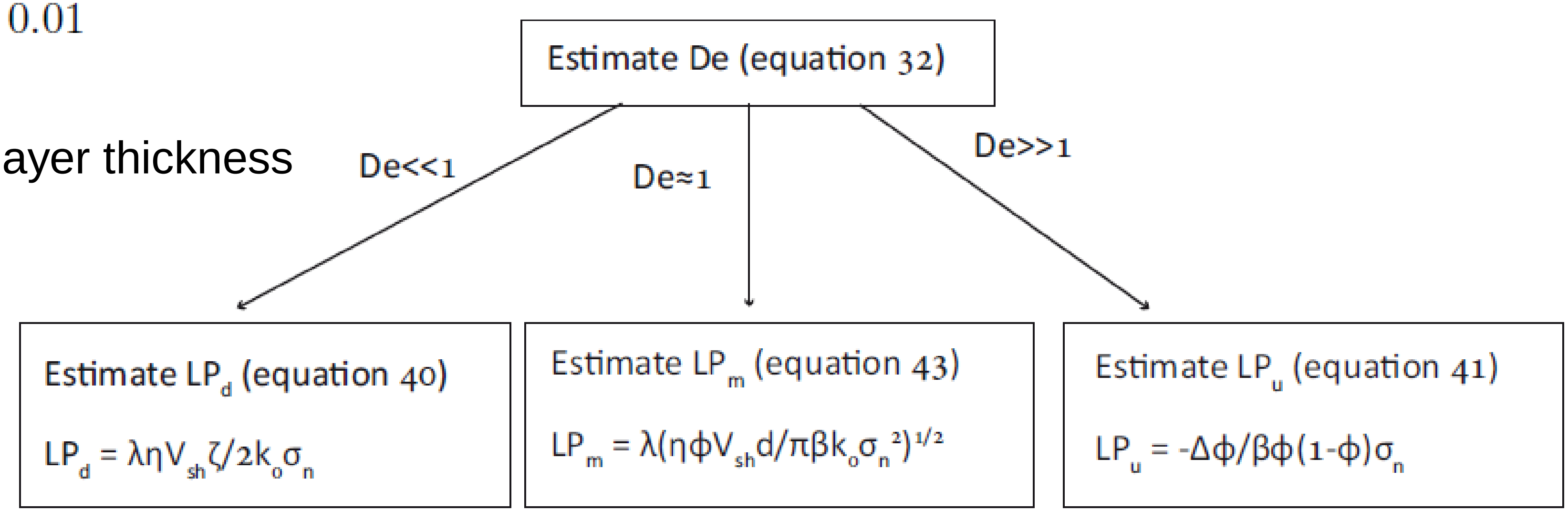


Figure 20: Diagram suggesting the path to estimate liquefaction potential for grains-fluid systems under shear.

Conclusions

- We have developed a fully coupled model for the coupled deformation of granular matrix and pore fluid pressurization and flow.
- We have identified two processes that control the evolution of PP:
  - Under undrained conditions – classical mechanism - PP rises due to pore volume compaction and PP drops due to pore volume expansion. Fluid compressibility is important.
  - Under drained conditions – ‘new’ mechanism – PP evolves as a function of instantaneous strain rate of pore volume.
- When the system is initially over-compacted:
  - Under drained conditions PP does not remember the initial dilatancy □ significant pressurization may take place later on.
  - Under undrained conditions we get only hardening upon dilation.