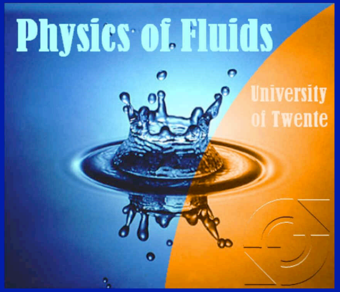
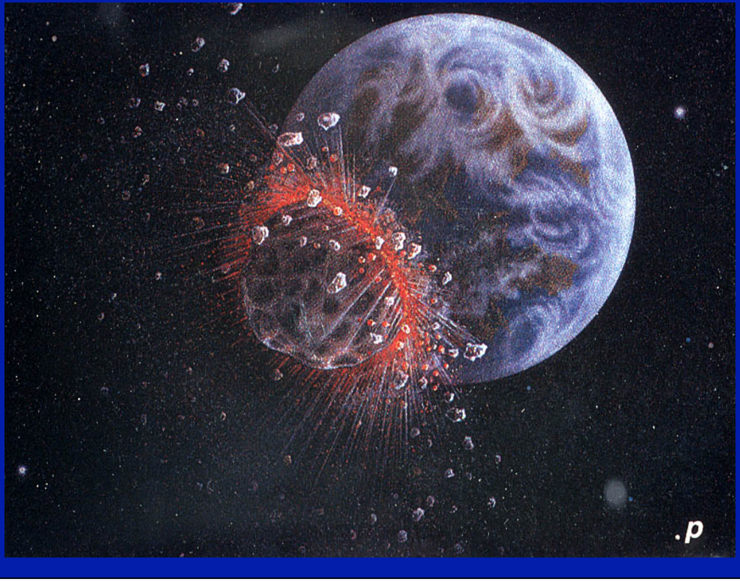
Impact:
Void collapse and jet formation

Detlef Lohse
Devaraj van der Meer
Raymond Bergmann
Gabriel Caballero



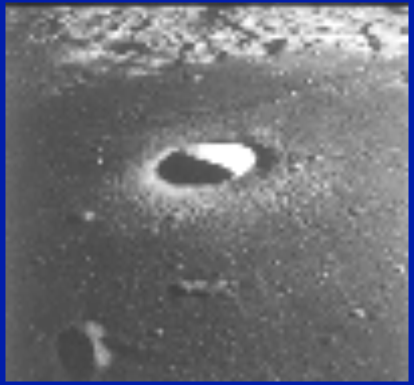
- Phys. Rev. Lett. 93, 198003 (2004)
- Nature 432, 689 (2004)
- Phys. Rev. Lett. 96, 154505 (2006)
- Phys. Rev. Lett. 99, 018001 (2007)

Astroid impact on earth

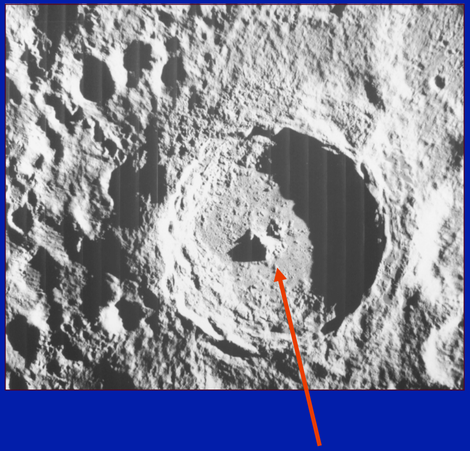


Craters

…on the moon



Moltke

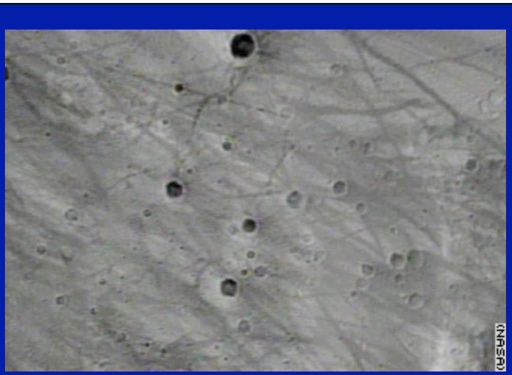


Tycho

central peak

Craters

…on Mars



Mars explorer,
January 2004

…on earth

Arizona

Speculation on crater formation

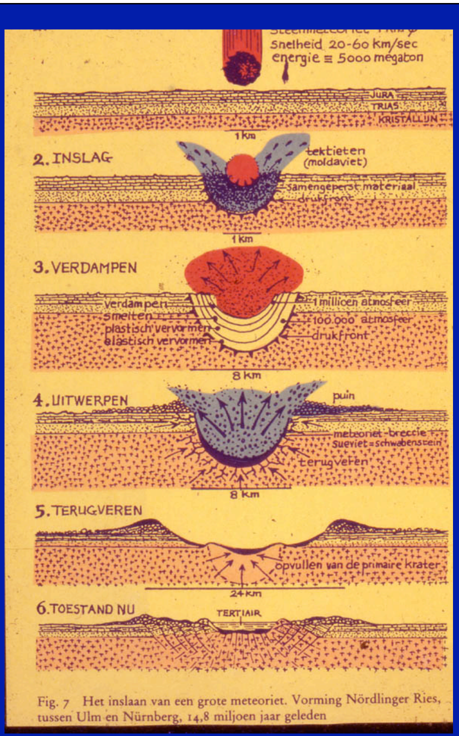


Fig. 7 Het inslaan van een grote meteoriet. Vorming Nördlinger Ries, tussen Ulm en Nürnberg, 14,8 miljoen jaar geleden

Source:
Jan Smit,
Amsterdam,
Dept. Geology

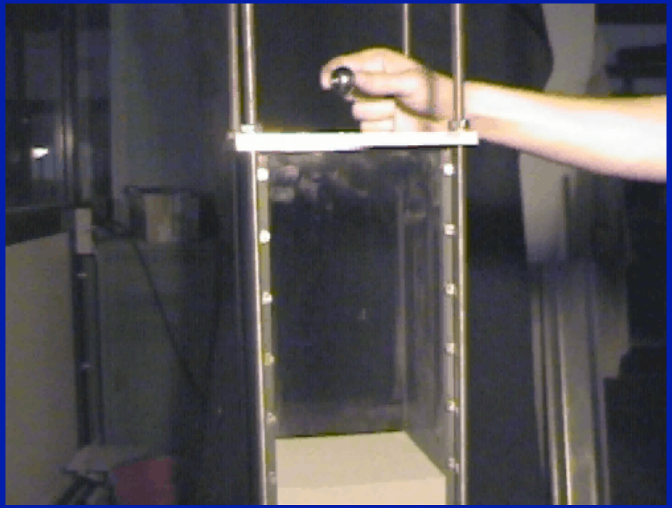
What’s really going on?

Downscaled experiments: Impact of steel ball on fine sand

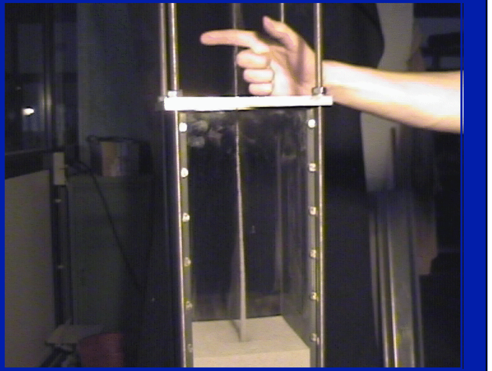
Problem: reproducibility

Controlled experiments

Ball dropped on **decompactified**, very fine sand



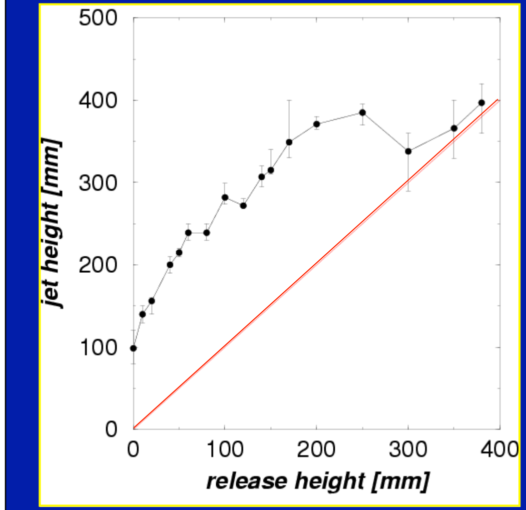
Ball at release point

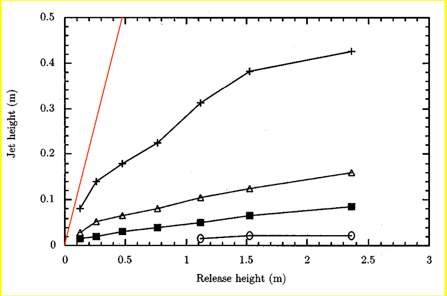


Maximum jet height

Jet height > Release height !

Jet height vs release height

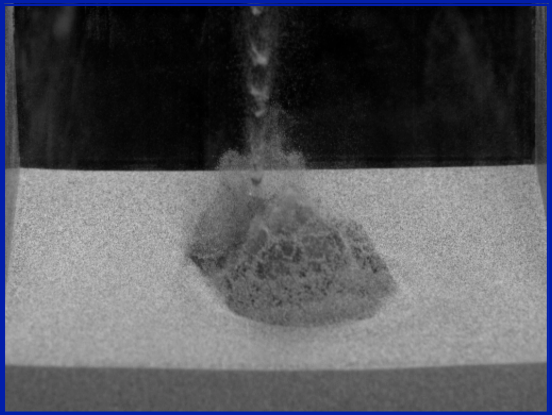




Siggi Thoroddsen,
and Amy Shen,
Phys. Fluids **13**, 4 (2001):

Impact of ball on decompactified sand

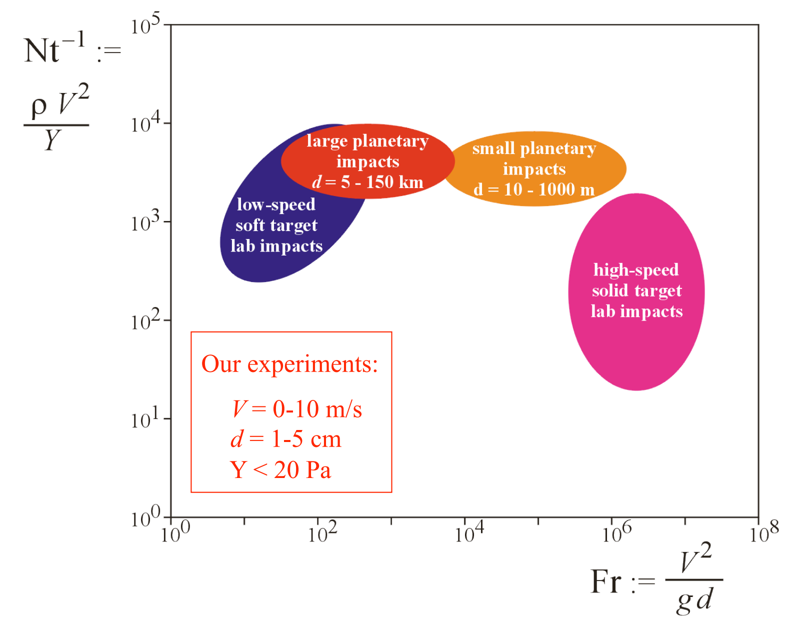
Impact of ball on decompactified sand



3 events:

- Impact creates splash
- A jet is formed
- Granular eruption

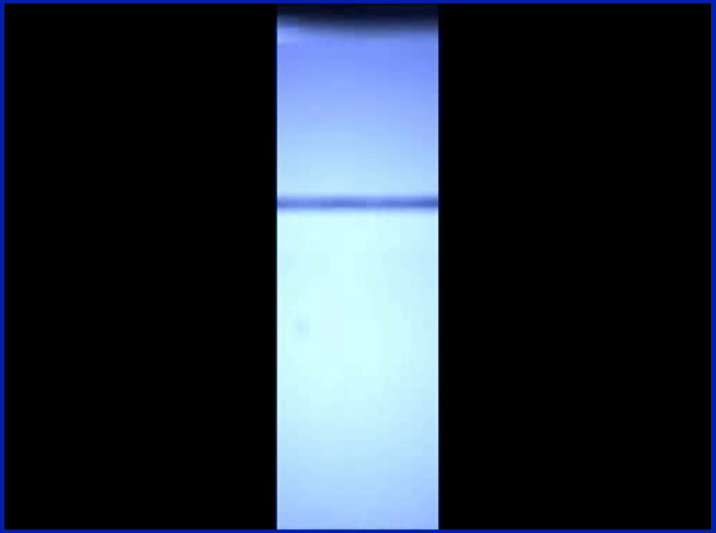
Impact: planetary vs. lab



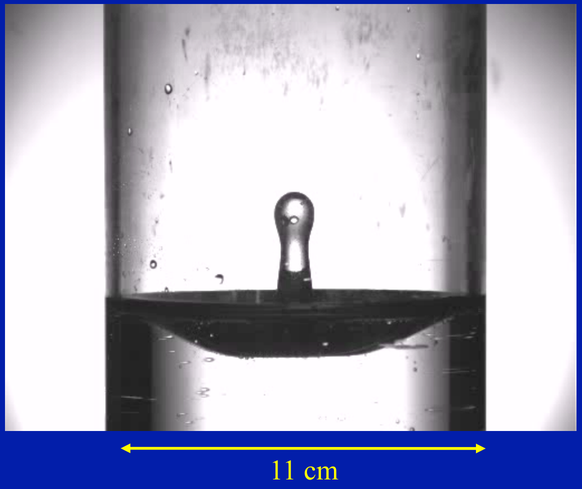
How to look into the sand?

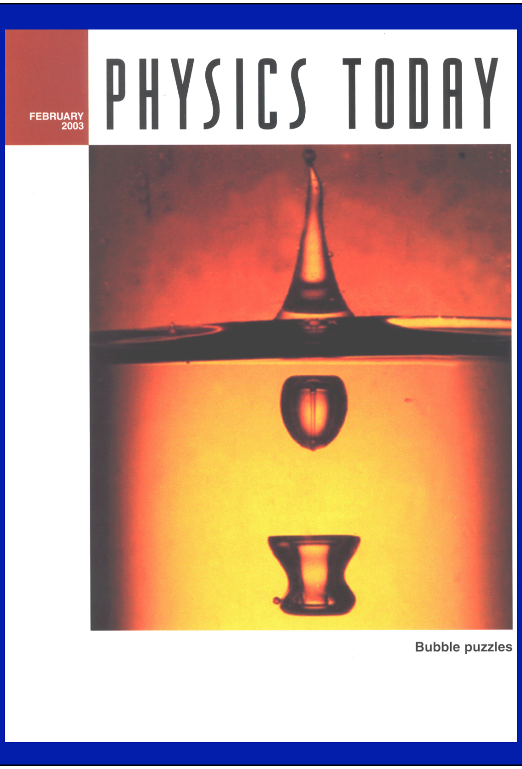
1. Analogy to (opaque) liquid
2. “2D” experiments (falling cylinder)
3. Discrete particle simulations

1. Ball or drop impact on water



Air entrainment through impact





Detlef Lohse
Phys. Today 56,
No. 2, p. 36 (2003)

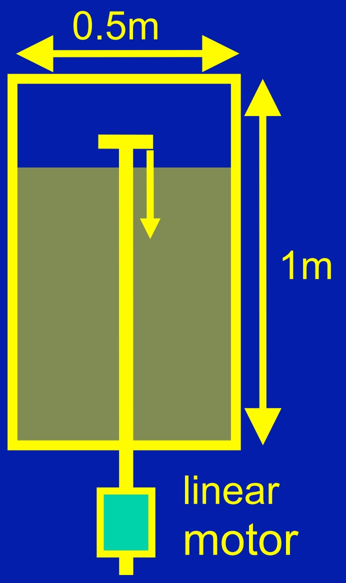
Mechanism

1. Void formation
2. Void collapse due to hydrostatic pressure
3. Jet formations at singularity point
4. Bubble formation

Quantitative analysis of void collapse in liquid

Phys. Rev. Lett. 96, 154505 (2006)

Pulled disk impacting on a liquid



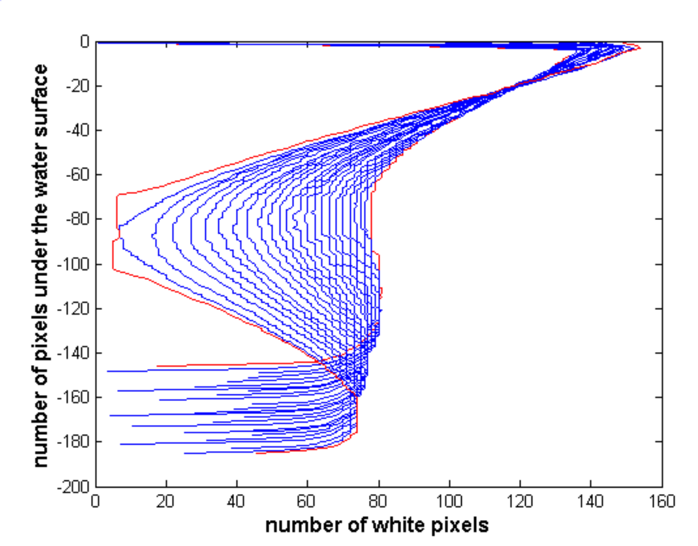
Pulled disk through a liquid

$v_{\mathrm{impact}} = 1.0$ m/s

$R_{\mathrm{disk}} = 0.03$ m

$\mathrm{Fr} = v^2_{\mathrm{impact}} / R_{\mathrm{disk}}\, g = 3.4$

Void profiles as function of time



Dimensional analysis

Relevant parameters:

- disk radius R_{disk}
- mean velocity V
- gravity g

Irrelevant parameters:

- surface tension (We)
- viscosity (Re)

$$Fr = \frac{V^2}{g R_{disk}}$$

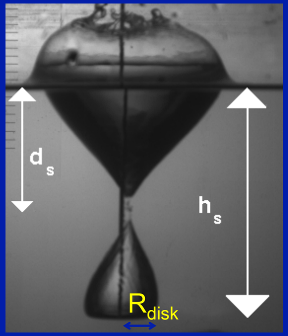
Dimensional analysis

Closure time $t_s \sim R_{disk}^{1/2} / g^{1/2}$

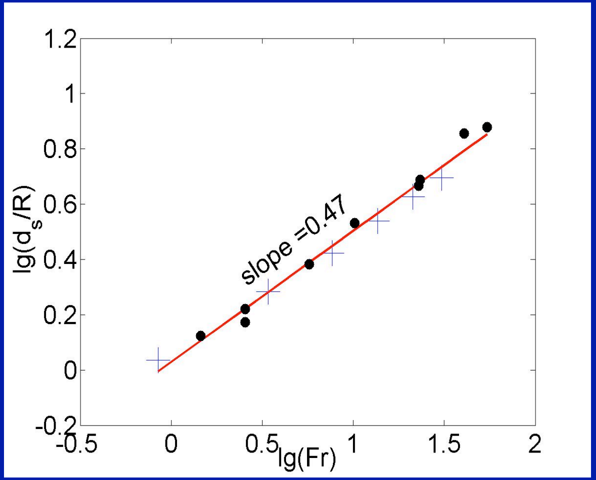
Depth at closure time $h_s \sim V\, t_s$

$$\frac{h_s}{R_{disk}} \sim Fr^{1/2}$$

$$d_s \sim h_s$$



Experimental & numerical scaling law



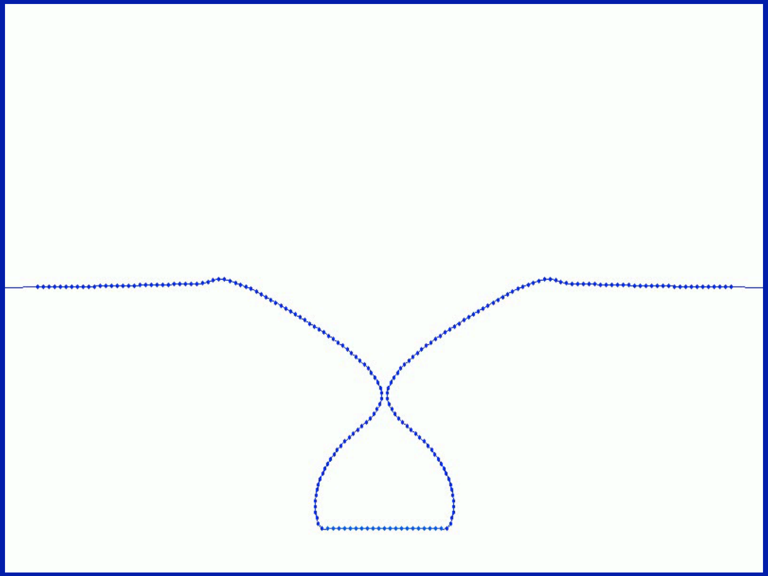
$h_s/R = 1.0\ Fr^{1/2}$

Boundary Integral simulation

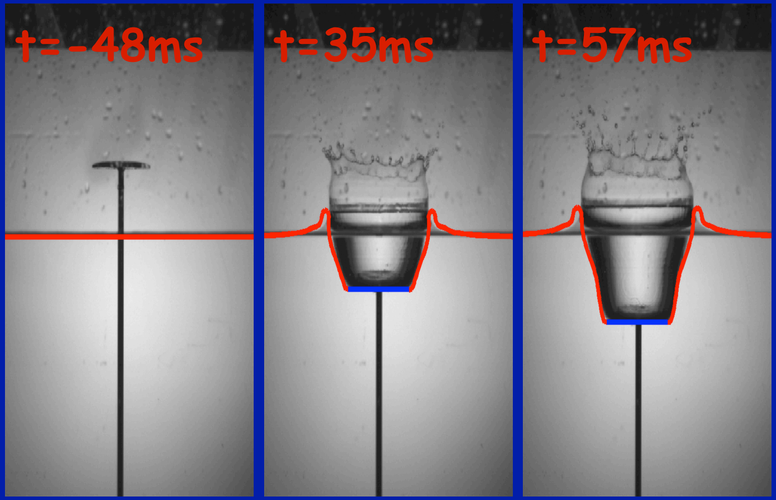
Potential theory

Fr = 7.8

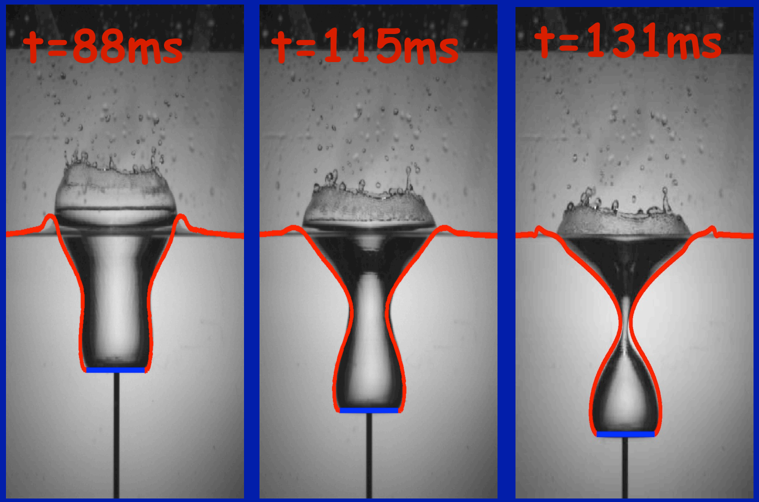
Boundary Integral simulation



Comparison BI simulation with experiment

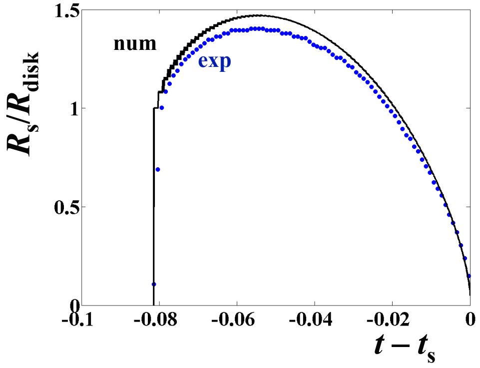


Comparison BI simulation with experiment



Simplified potential flow analysis:
2D Rayleigh-Plesset equtation

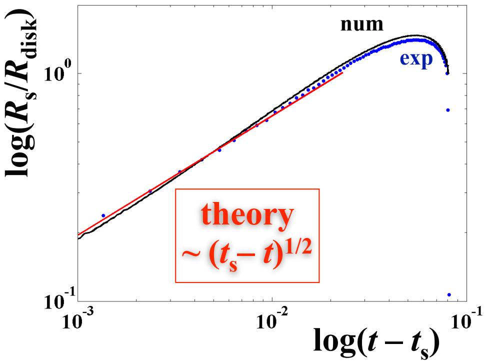
Rayleigh-type singularity t --> t_s



$$(h\ddot{h}+\dot{h}^2)\log\frac{h}{h_\infty}+\tfrac{1}{2}\dot{h}^2=gd_s$$

$$(h\ddot{h}+\dot{h}^2)=\frac{d^2}{dt^2}\left(h^2\right)=0$$

$$\frac{h}{R_{disk}}\propto\left(t_s-t\right)^{1/2}$$



At the end, ln to –inf neglect the rest, simplifies, great agreement

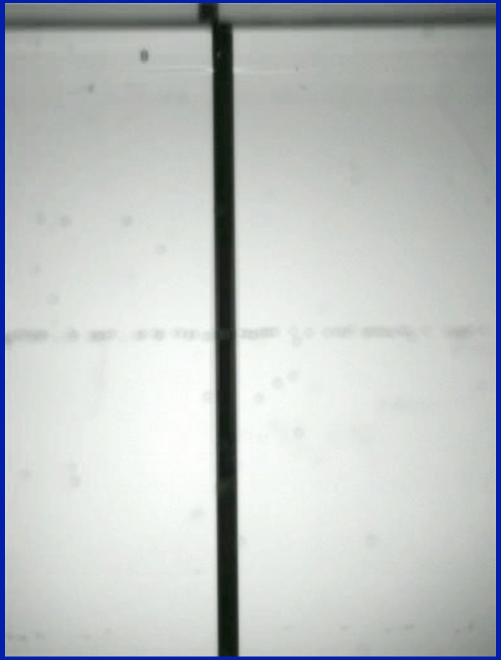
Slow impact:

Toroidal bubble!

$v_{\text{impact}} \approx 0.5$ m/s

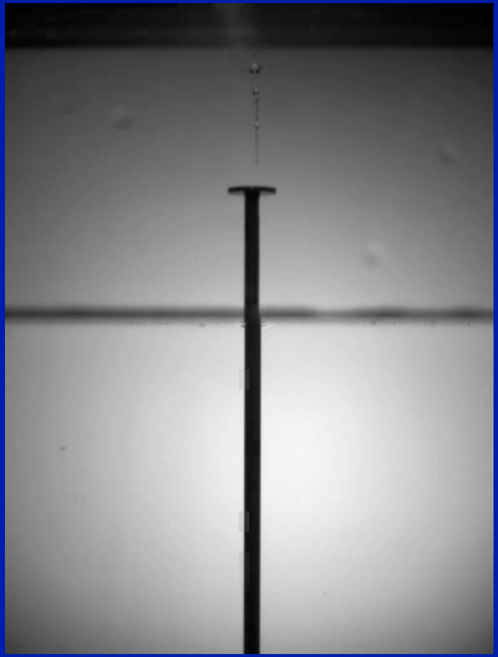
$R_{\text{disk}} = 0.03$ m

Fr = 0.8



Fast impact:

Surface seal

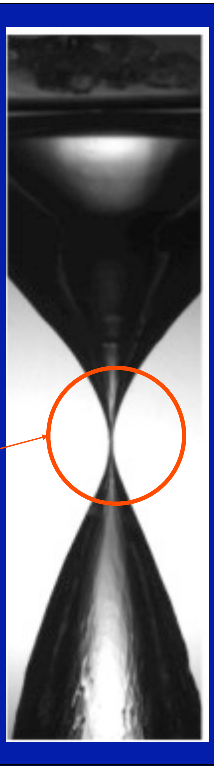


$v_{\text{impact}} \approx 3$ m/s

$R_{\text{disk}} = 0.01$ m

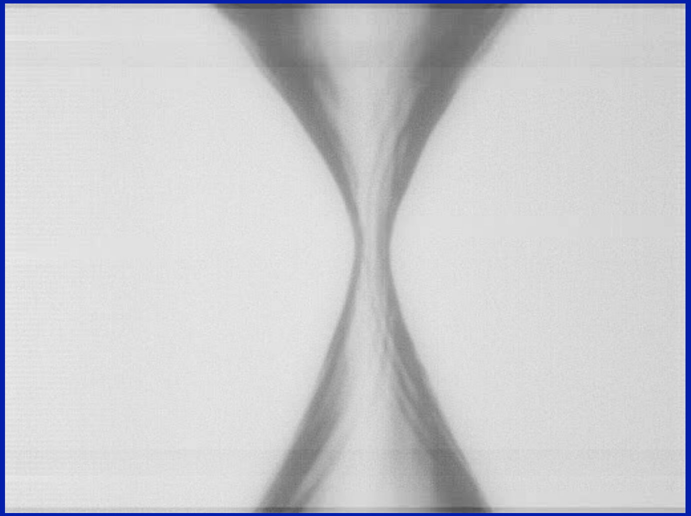
Fr = 100

What exactly happens at collapse?

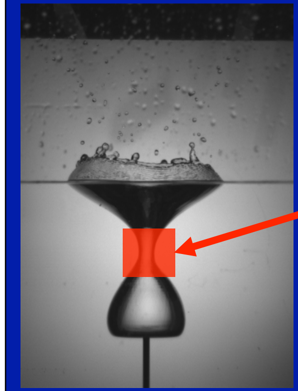


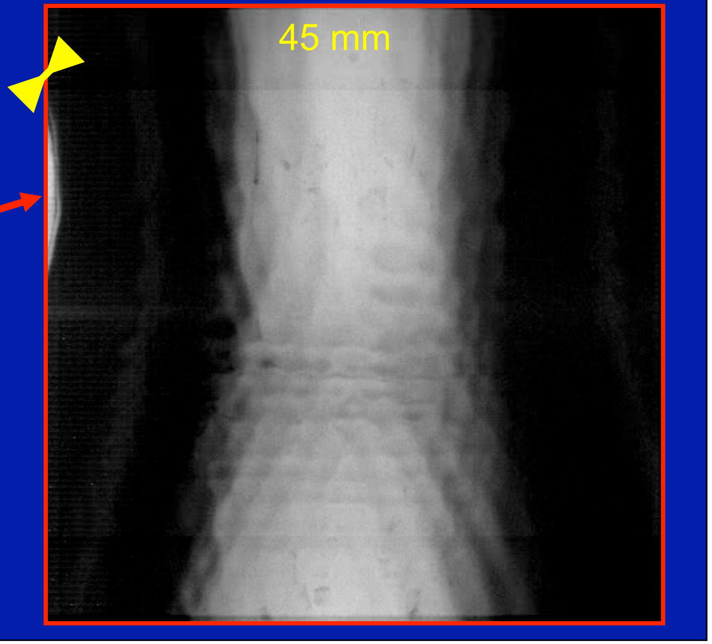
singularity

Focusing of energy → jets



Very close to pinch-off

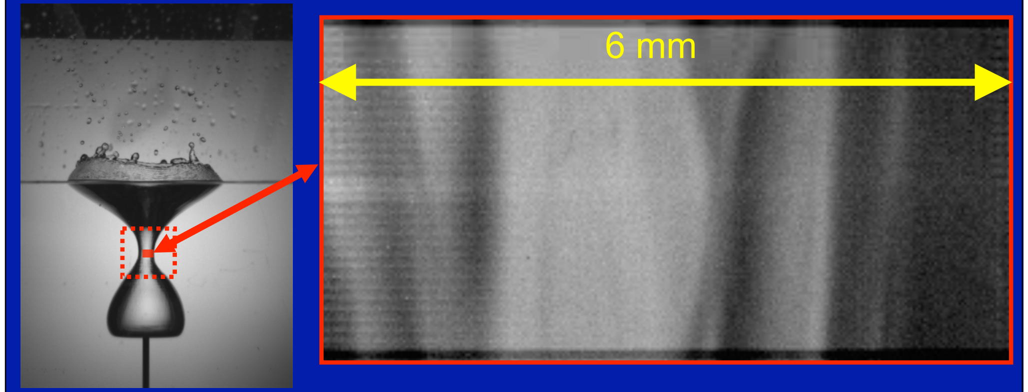




$H_{disk} = 0.03$ m
$V_{impact} = 1.0$ m/s
12800 fps

Zoom in, to increase 12.8 fps, capillary waves, instrability

Even closer to pinch-off



$H_{disk} = 0.03$ m
$V_{impact} = 1.0$ m/s

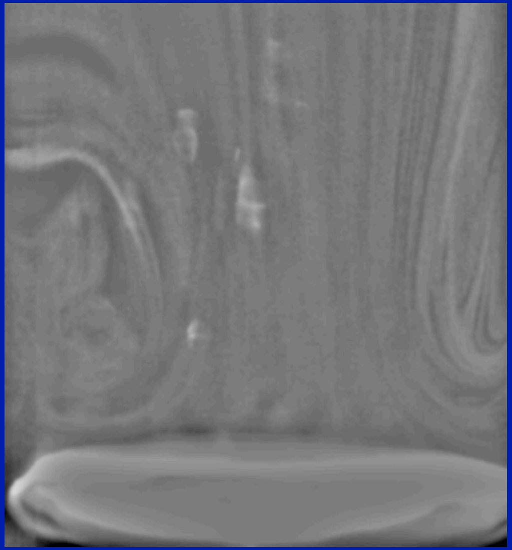
48000 fps

1. Capillary instability?
2. Instability through fast air-flow?

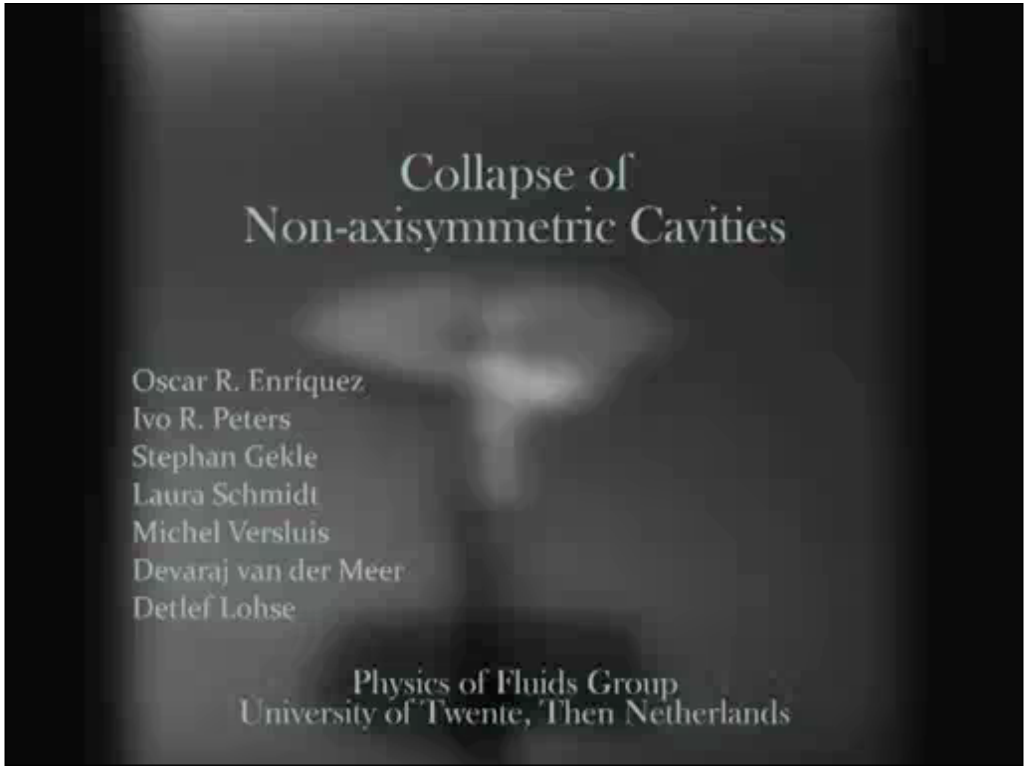
Instability clearer, 48 fps, air rushing out, Kelvin Helmholtz, frequency bubble cloud +/- 10 kHz, 1 mm bubble radius, pure lyinertial collapse of the neck

Outwards airflow in the end

Flow visualization
with smoke particles



Air flow reverses!



Collapse of Non-axisymmetric Cavities

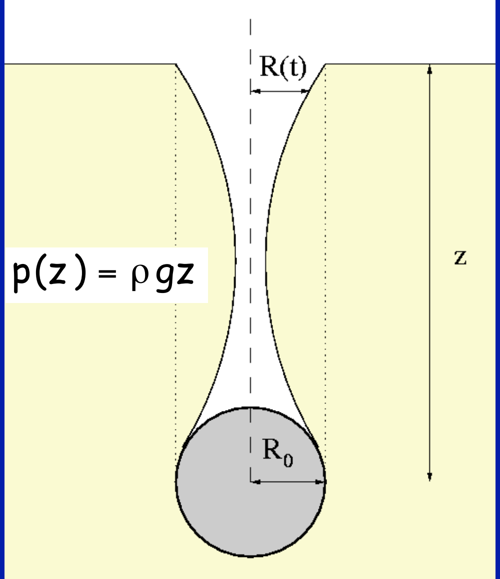
Oscar R. Enríquez
Ivo R. Peters
Stephan Gekle
Laura Schmidt
Michel Versluis
Devaraj van der Meer
Detlef Lohse

Physics of Fluids Group
University of Twente, Then Netherlands

Back to granular matter:

Rayleigh-Plesset type model
for collapse of sand void

Cavity collapse



Initial conditions

$$R(z, t_{pass}) = R_0$$

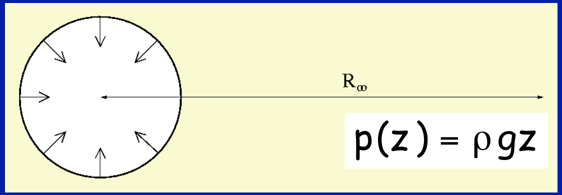
$$\dot{R}(z, t_{pass}) = 0$$

Sand pressure

$$p(z) = \rho g z$$

Rayleigh-type dynamics of cavity collapse

2D slice at depth z



$$p(z) = \rho g z$$

Euler equation in cylindrical coordinates

$$\partial_t v + v\,\partial_r v = -\frac{1}{\rho}\partial_r p$$

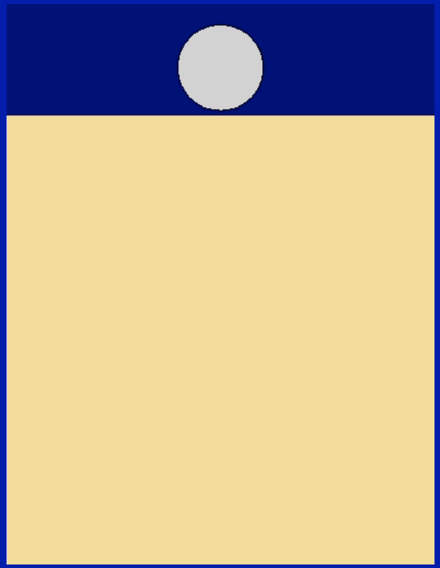
Continuity equation and boundary conditions

$$r\,v(r) = R(t)\,\dot{R}(t)$$

Equation for 2D collapsing void

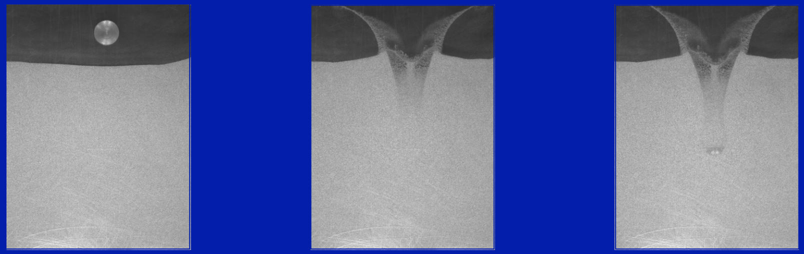
$$(R\ddot{R} + \dot{R}^2)\ln\left(\frac{R}{R_\infty}\right) + \tfrac{1}{2}\dot{R}^2 = gz$$

Rayleigh model at high impact velocity

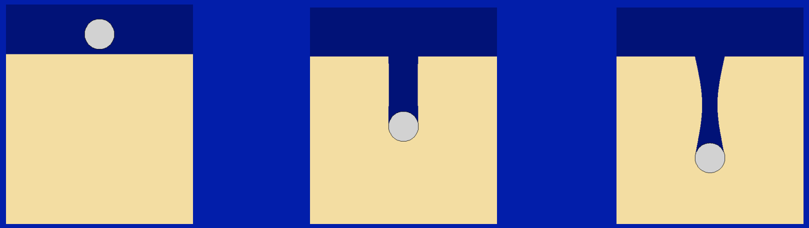


bubble formation !

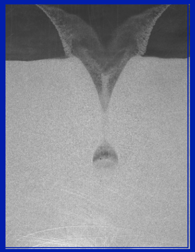
Experiments vs. hydrodynamic theory



T = -21ms T = 37ms T = 78ms



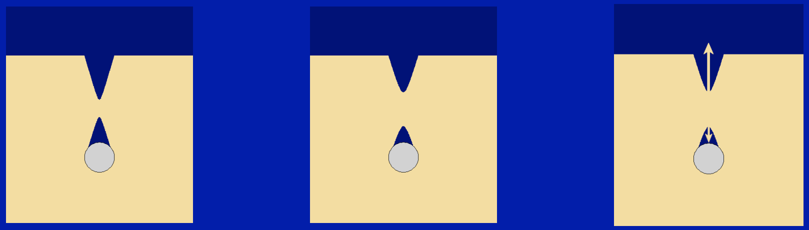
Experiments vs. hydrodynamic theory



T = 100ms

T = 116ms

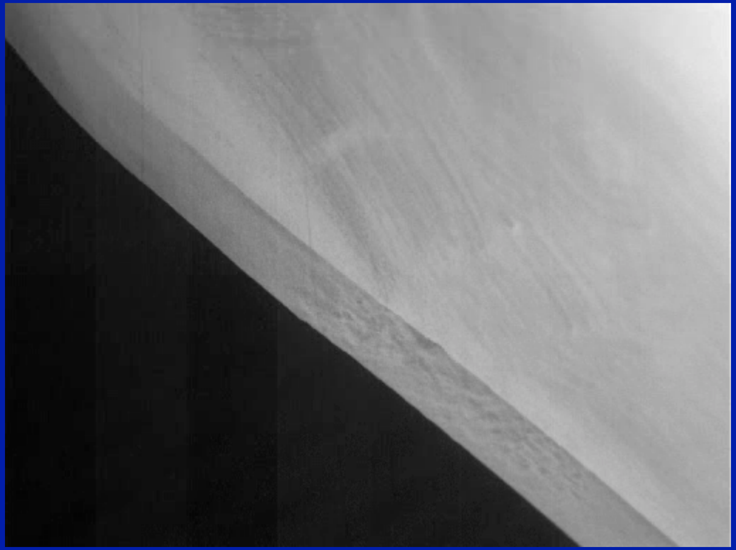
T = 191ms



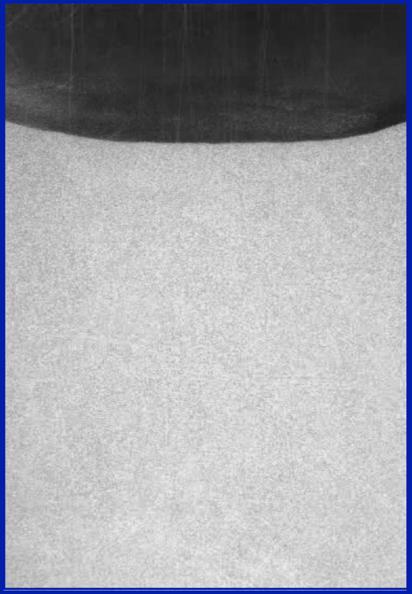
How to look into the sand?

1. Analogy to water
2. **“2D” experiments (falling cylinder)**
3. Discrete particle simulations

2D experimental setup



2D experiment: high impact velocity



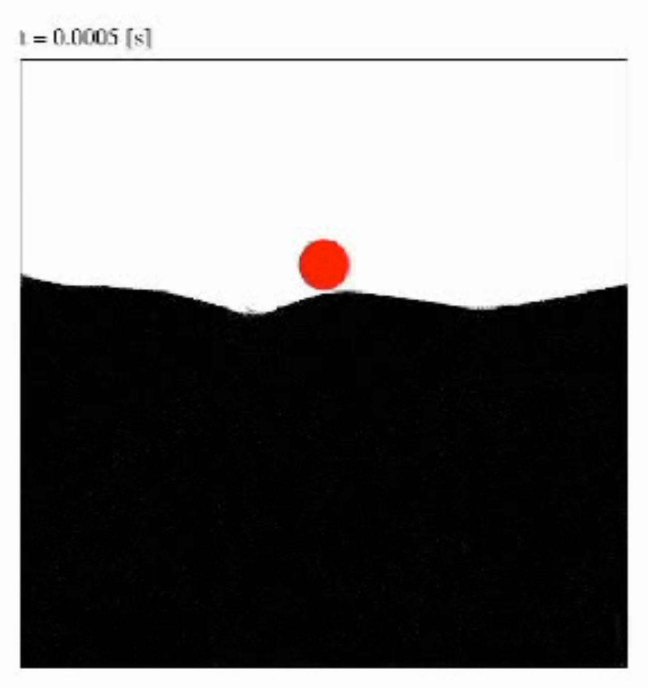
Just as in water:

1. void formation
2. void collapse
3. two jets (sheets in 2D)
4. bubble formation

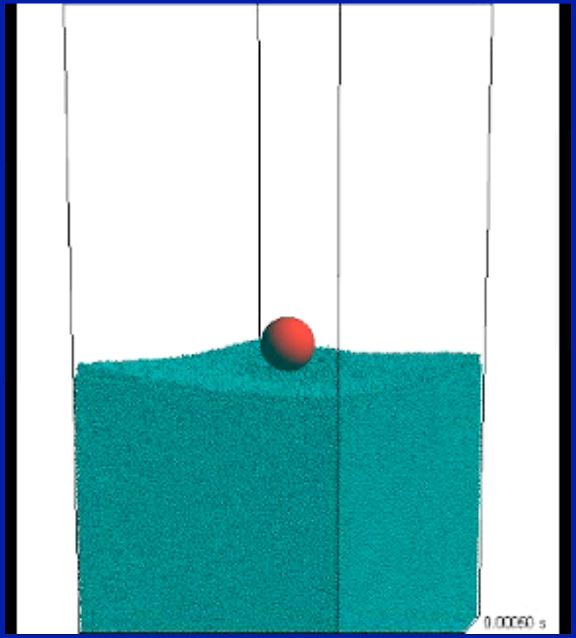
3. Discrete particle simulations

- soft sphere code
- $N = 1000000$
- $d_s = 0.5$ mm
- $d_b = 15$ mm
- quasi 2D (8 grains thick)
- pre-fluidized

Discrete particle simulation



3D discrete particle simulation

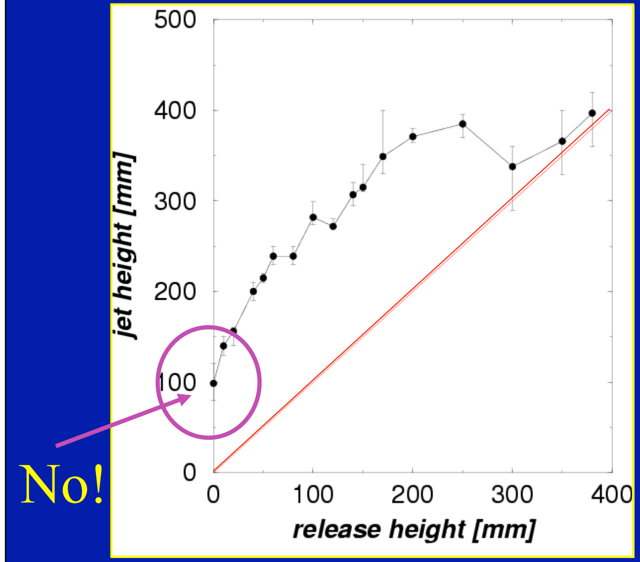


Does sandbed support weight?

D. Lohse, R.Rauhe, D. van der Meer, R. Bergmann, Nature 432, 689 (2004)

Sandbed does not support weight

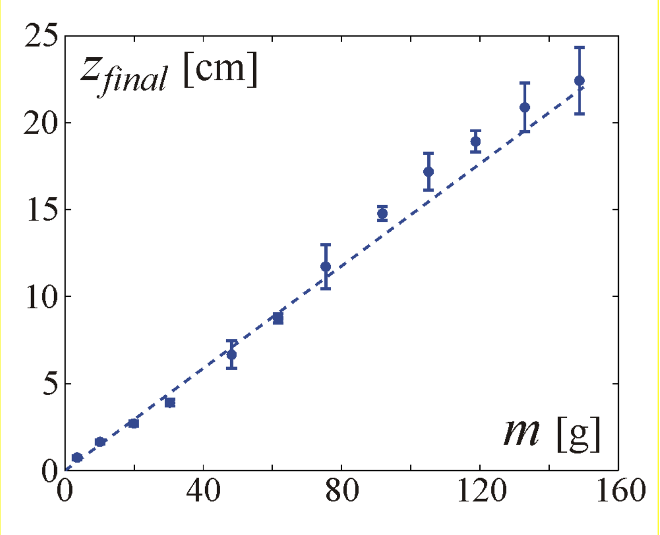
“Dry quick sand”



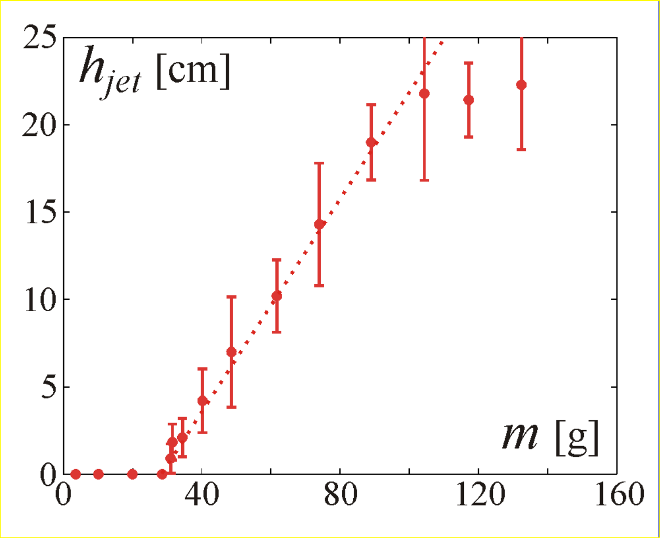
Packing density
only 41% !

Myth from Lawrence of Arabia…

final depth ~ mass



Jet height vs mass: threshold behavior



A force model to explain the observations

Model: Coulomb friction

Coulomb friction $F_{coulomb} = -\kappa z$

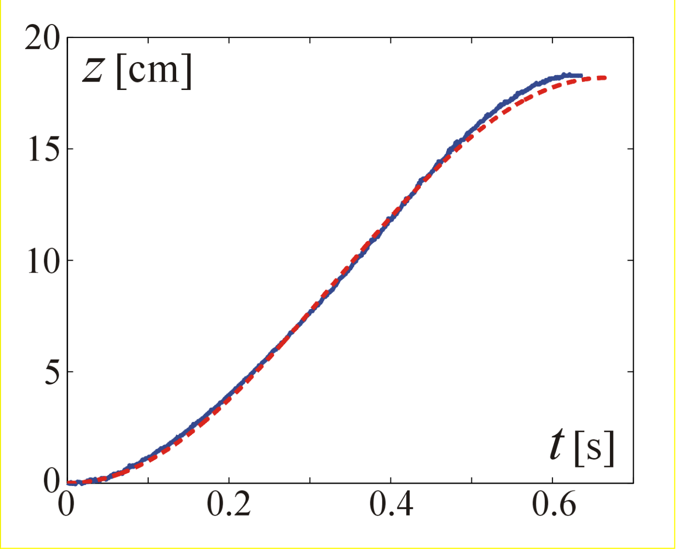
Force balance $(m + m_A)\ddot{z} = mg - \kappa z$

Solution $z(t) = \frac{1}{2} z_{final} (1 - \cos \omega t)$?

Final depth $z_{final} = \dfrac{2mg}{\kappa}$ ✓

$$\omega = \sqrt{\frac{\kappa}{m + m_A}} \qquad 0 \le t \le \frac{\pi}{\omega}$$

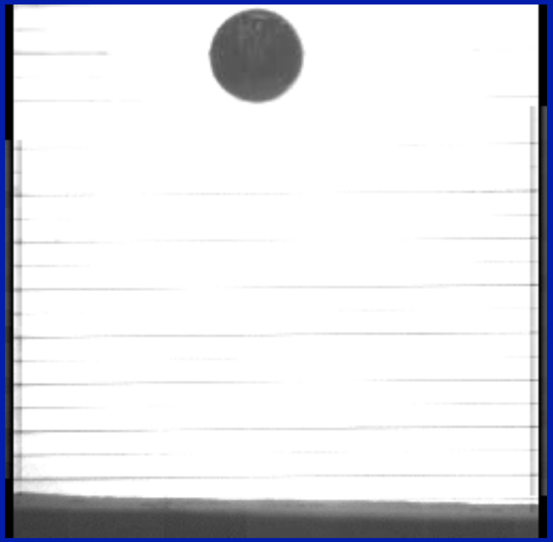
Depth vs time



experiments + model

Large-Fr impact on sand

Surface seal,
just as in
water



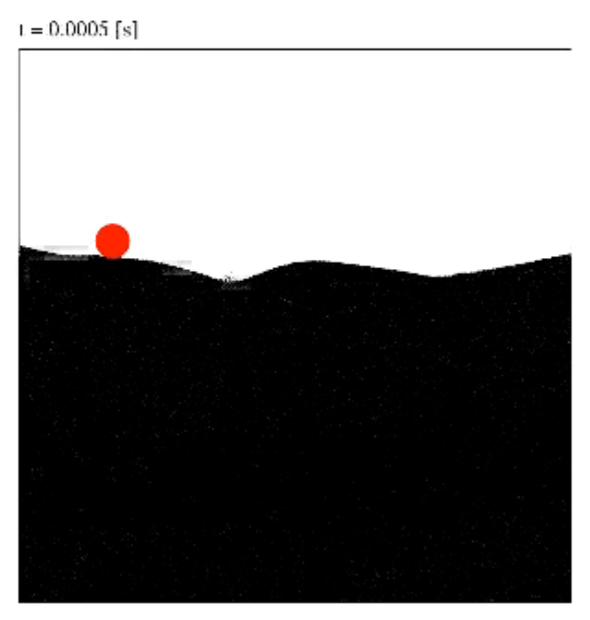
Oblique impact

Oblique impact

45°

v = 3.7m/s

Oblique impact



45°

v = 3.7m/s

Conclusions

Series of events in both liquid and sand:

1. void formation
2. void collapse
3. two jets
4. bubble formation

Hydrodynamic description seems to work at least semiquantitatively (for soft sand)

D. Lohse *et al.*, Phys. Rev. Lett. 93, 198003 (2004)

Granular void collapse analyzed by…

- Experiment
- Analogy to liquid
- Boundary Integral simulations
- Dimensional analysis
- Discrete particle simulations
- Simple continuum Rayleigh type model

Breakdown of hydrodynamic description

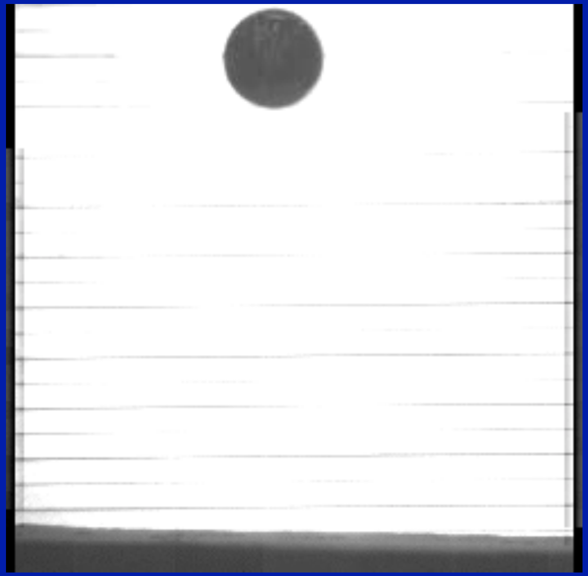
… at large enough **compactification** of sand when strong enough **force chains** will have built up.

But how?

- sudden breakdown?
- continuous breakdown?

Is this the full story?

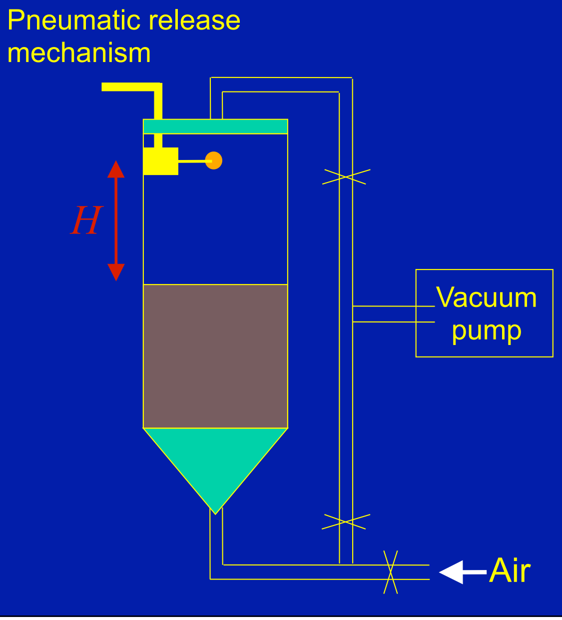
Large-Fr impact on sand



Surface seal

Fr=100

Analyse effect of ambient air



Effect of ambient pressure on…

- … splash
- … jet
- …penetration depth

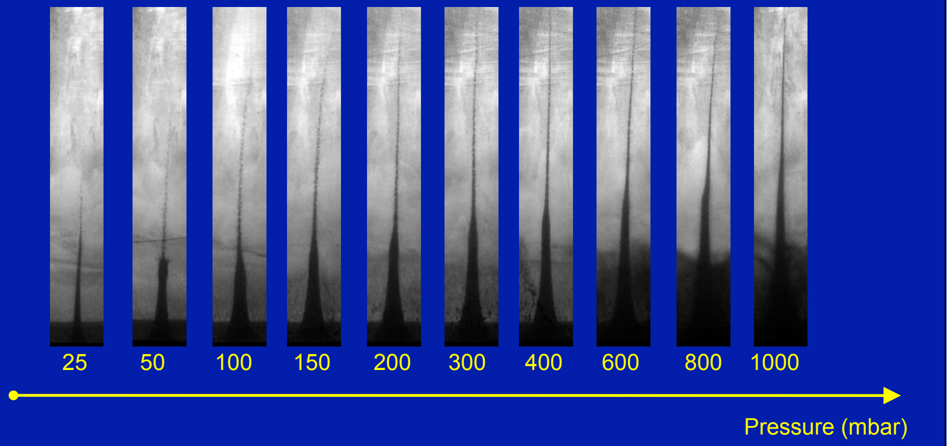
Splash depends on ambient pressure

Ejectie 9 mbar calibratie

Jet much less pronounced under reduced pressure!

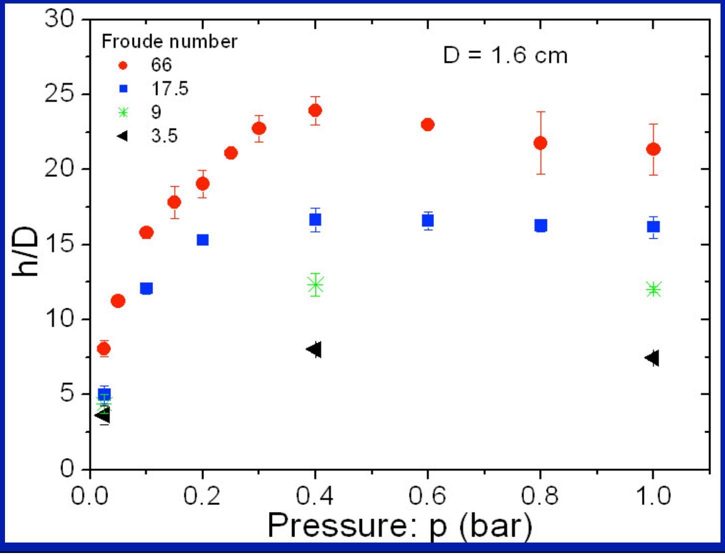
see also Royer et al.,
Nature Phys. 1, 164 (2005)

Effect of ambient air pressure

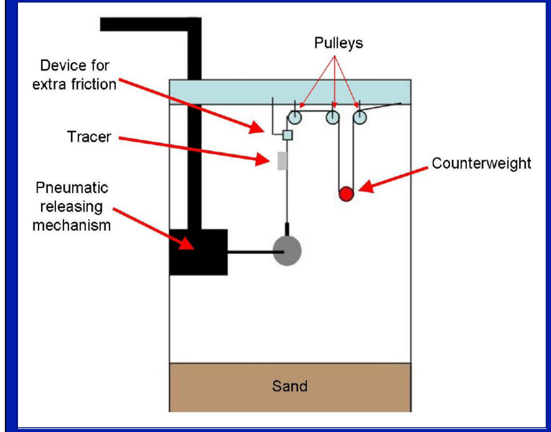


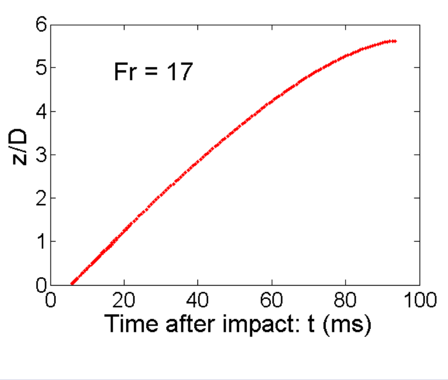
D = 2.5cm ; Fr = 32 ; t = 159ms

Jet height vs ambient pressure: saturation effects: two regimes

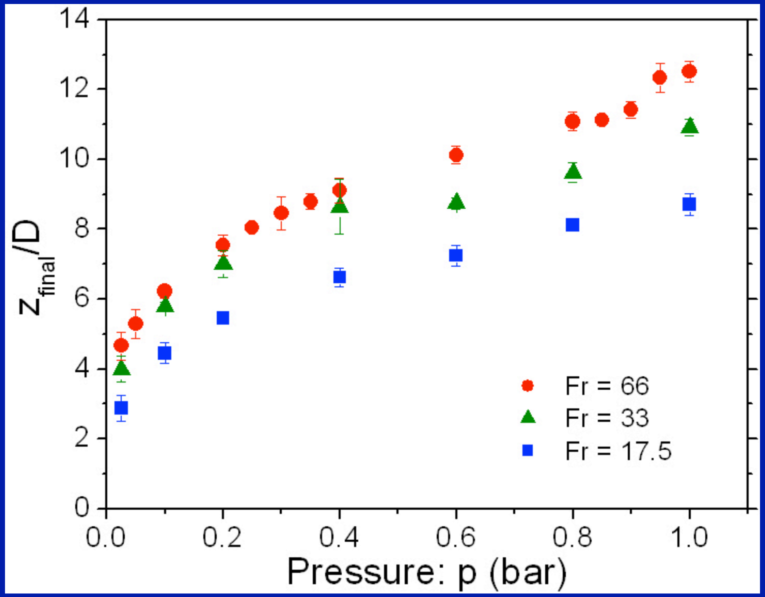


Ball trajectory in sand

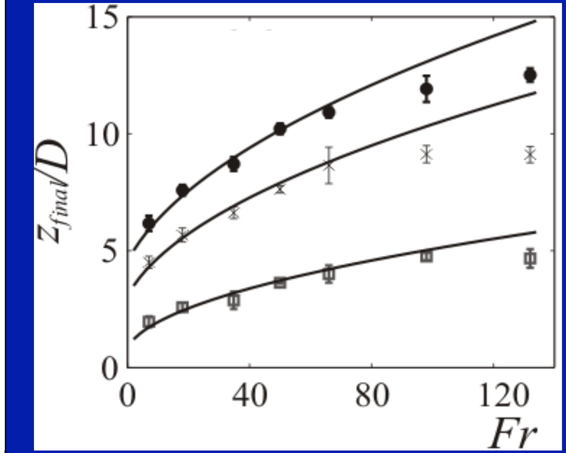




Final depth of intruder vs p



Final depth described by force balance model



1000 mbar

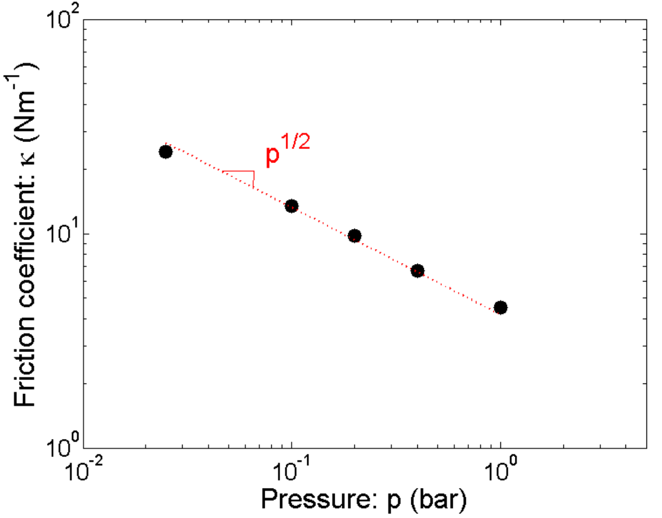
400 mbar

25 mbar

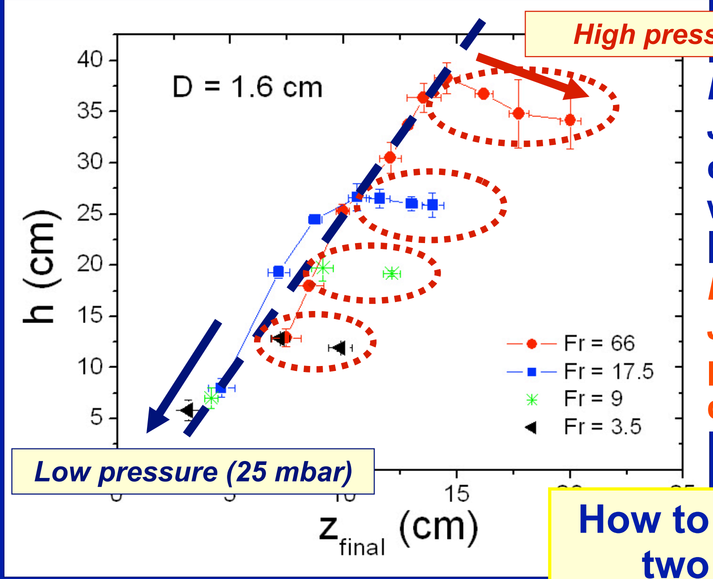
$$m\ddot{z} = mg - \kappa z,$$

$$z_{final} = \frac{gm}{\kappa}\left(1 + \sqrt{1 + \frac{\kappa D \mathrm{Fr}}{2\mathrm{gm}}}\right)$$

Coulomb friction coefficient depends on ambient pressure



Final depth correlated with jet height



High pressure (1 bar)

Low pressure (25 mbar)

Two regimes:

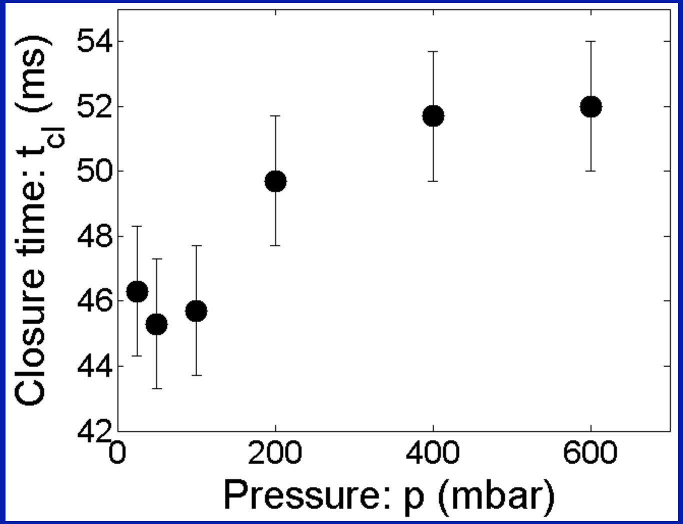
Regime 1 (low p):
Jet height increases linearly with final depth

Regime 2 (high p):
Jet height independent of final depth

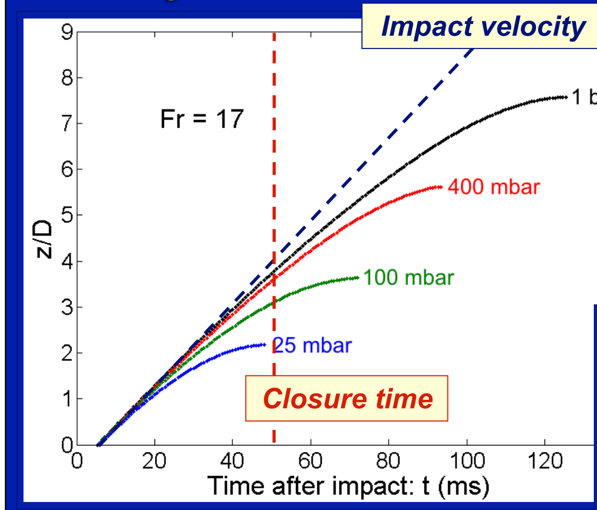
How to explain these two regimes ?

Closure time

Closure time: nearly constant

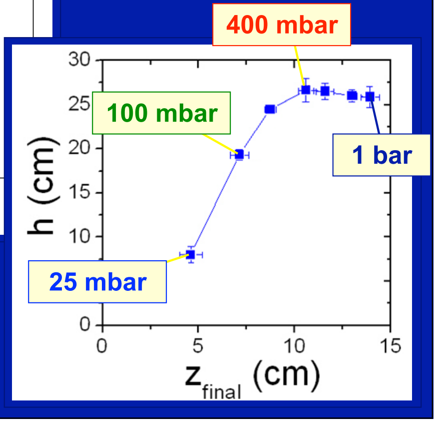


Trajectories: when closure?



High pressures:
Identical trajectories until closure time
→ *same jet height (regime 2)*

Low pressures:
Trajectories deviate substantially
→ *final depth determines jet height (regime 1)*

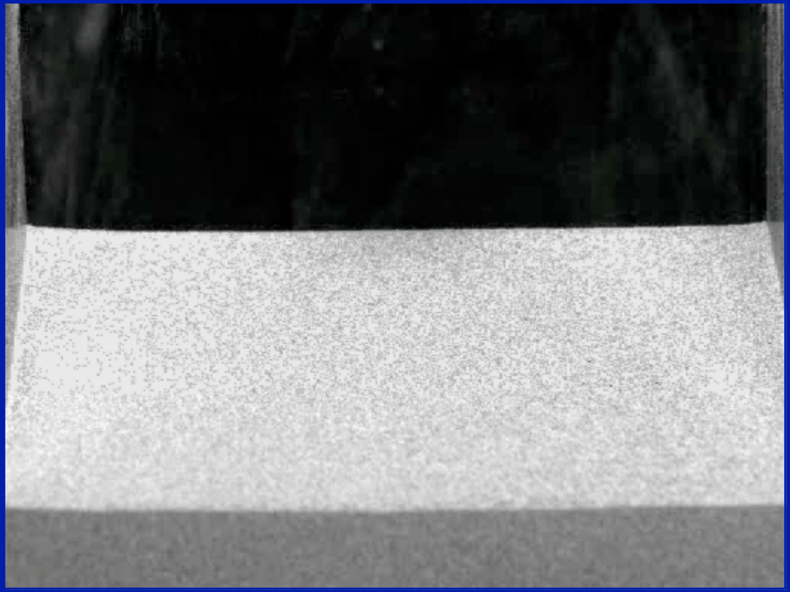


Final question:

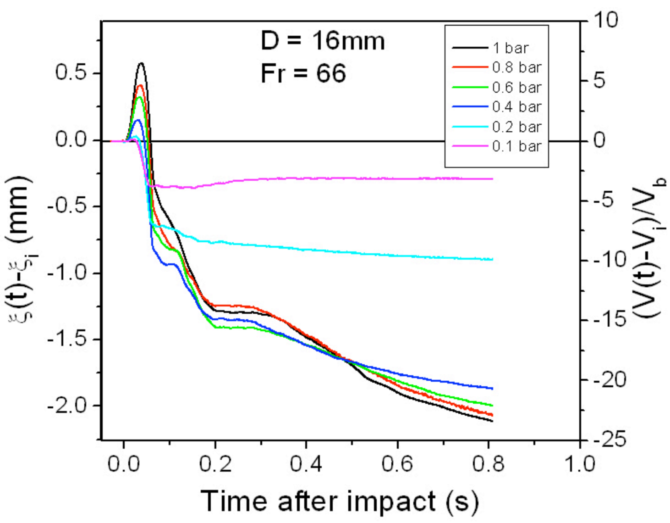
What causes the sphere to penetrate less at lower pressures (i.e., the friction reduction)?

The sand bed is fluidized by the air flow around the impacting ball ($Re_{\text{sand grains}} \approx 5$)!

Impact of ball on decompactified sand



Height of sand bed vs time at impact



Ambient air leads to expansion of granular bed at impact: **extra fluidization**

Conclusions II

- Ambient air pressure strongly influences the penetration depth of the ball and thus the jet height
- Ambient air pressure hardly affects the collapse of the cavity
- Two regimes:
  - high p: trajectories unchanged up to closure
  - low p: trajectories deviate: jet height <-> depth
- Autofluidization effect

Gabriel Caballero et al., Phys. Rev. Lett. 99, 018001 (2007)

Collaborators:

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- Hans Kuipers
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- Rene Mikkelsen
- Andrea Prosperetti
- Remco Rauhe
- Marijn Sandtke
- Mark Stijnman
- Michel Versluis
- Ko van der Weele
- Christiaan Zeilstra

Financial support from **FOM**

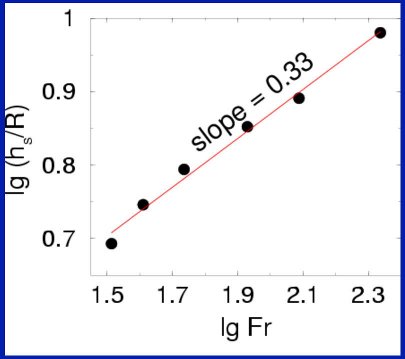
Scaling for position of singularity

$t_{touch}(z)=t_{get}(z) + t_{collapse}(z)$

Minimize:

$\rightarrow \quad h_s(Fr) \sim Fr^{1/3}$

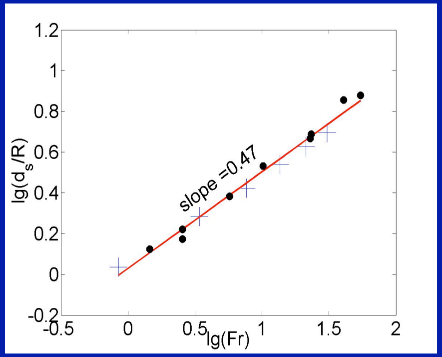
Different from scaling law in water!



$h_s/R = 0.69\ Fr^{1/3}$

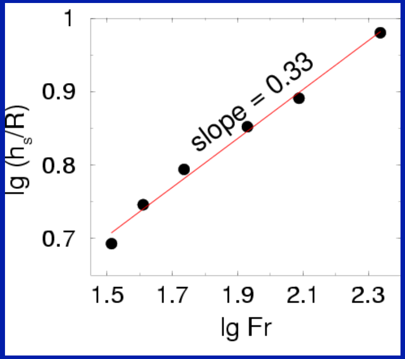
Different scaling laws!

water



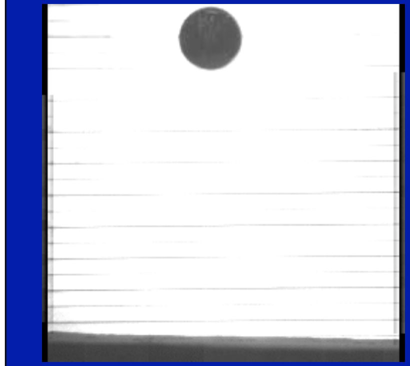
$$h_s/R = 1.0\ Fr^{1/2}$$

sand



$$h_s/R = 0.69\ Fr^{1/3}$$

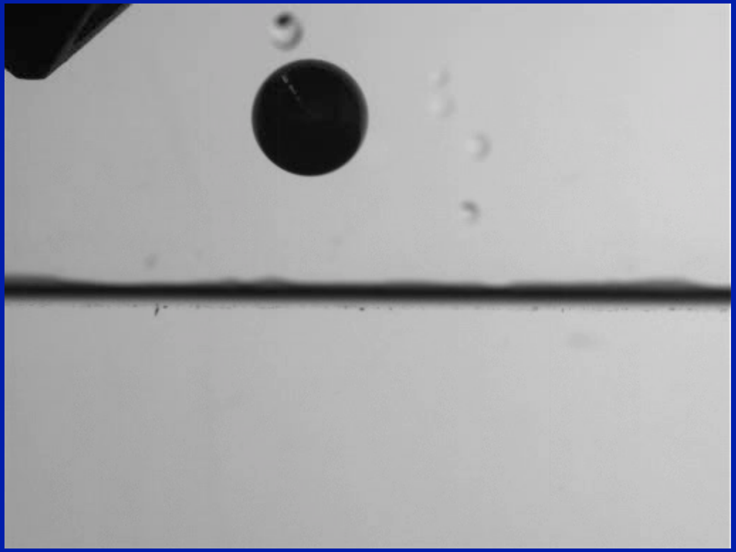
High velocity impacts



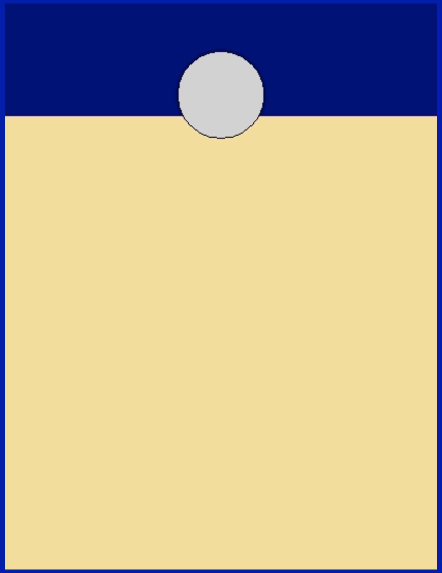
v = 3.6 m/s

v = 2.0 m/s

Oblique impact on water

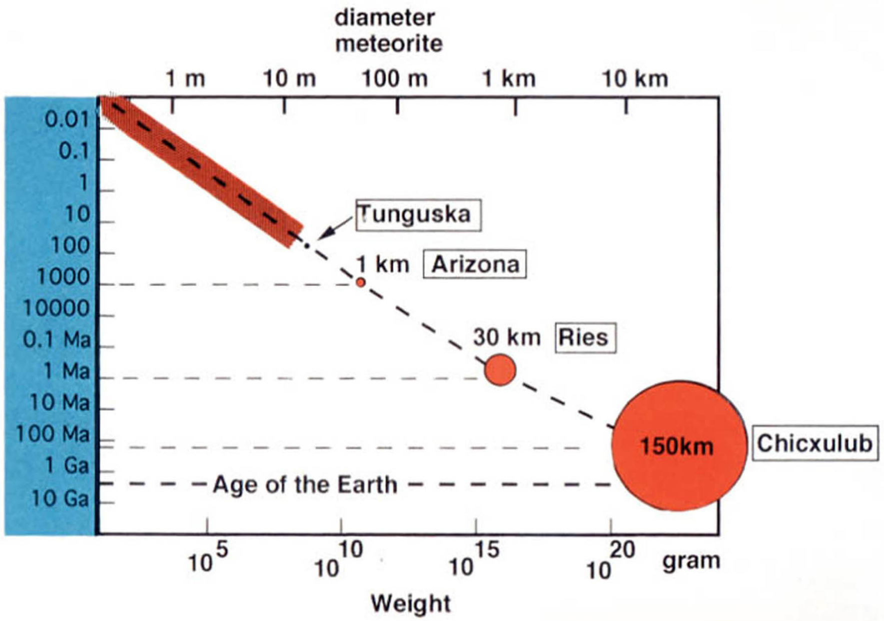


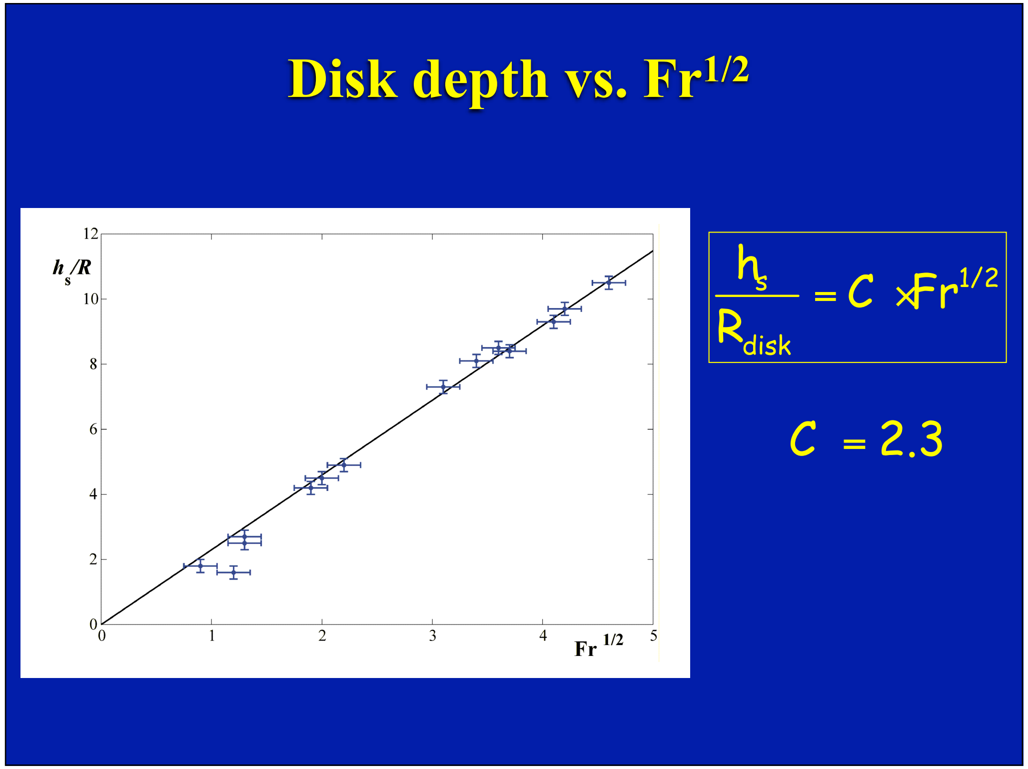
Rayleigh model: low impact velocity



Collapse without air entrainment

Impact frequency on the surface of the Earth





Disk depth vs. $Fr^{1/2}$

$$\boxed{\frac{h_s}{R_{disk}} = C \times Fr^{1/2}}$$

$$C = 2.3$$

I'M NOT AT ALL SURE ABOUT THE EQUALITY. CHECK MCMAHON & GLASHEEN FOR THEIR DEFINITION OF <v>!!!!!!

Again refer to the big feet of the lizard.

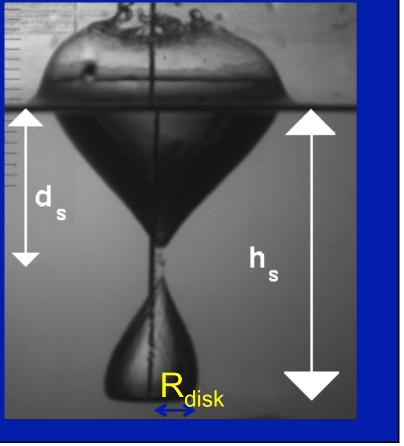
Dimensional analysis

Closure time $t_s \sim R_{disk}^{1/2} / g^{1/2}$

Depth at closure time $h_s \sim V\, t_s$

$$\boxed{\frac{h_s}{R_{disk}} = C \times Fr^{1/2}}$$

$d_s \sim h_s$



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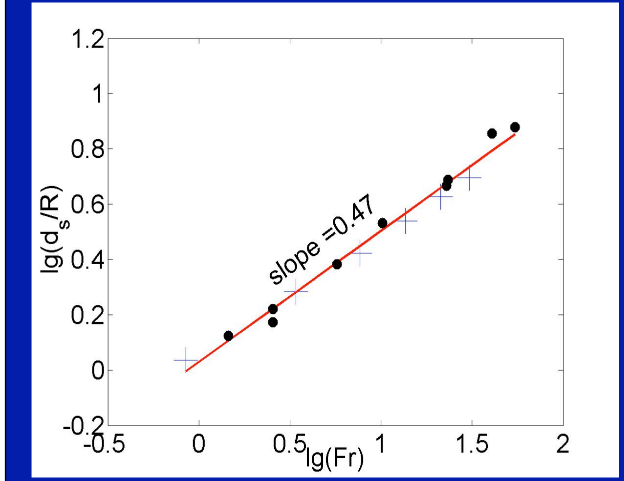
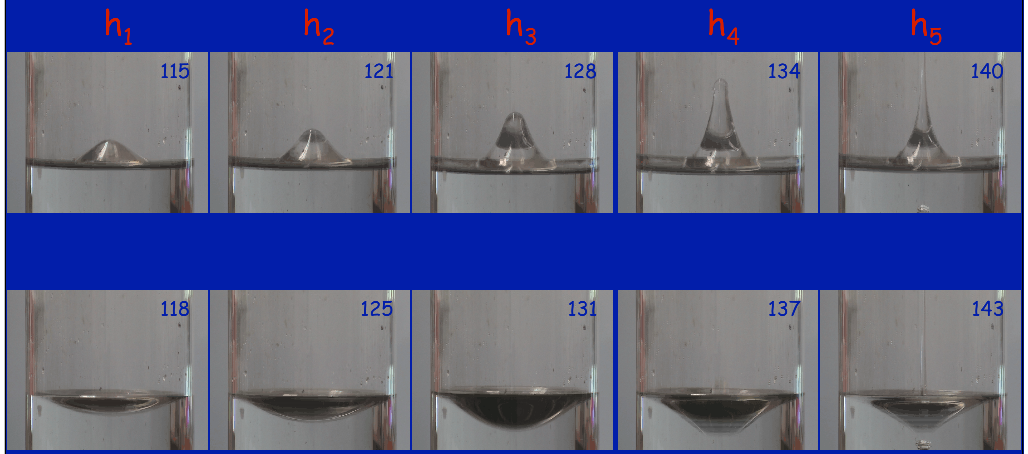
Experimental & numerical scaling law



$$h_s/R = 1.0\ Fr^{1/2}$$

Air entrainment by shaking fluid: The Faraday experiment

Parametric instability



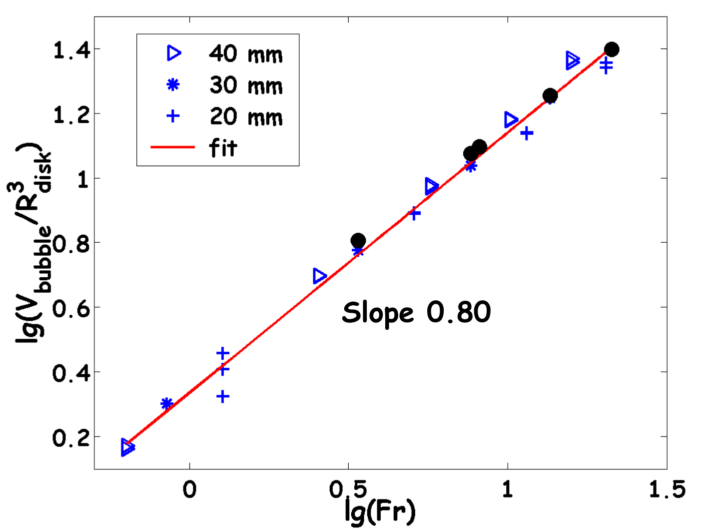
How much air is entrained?

Void profile just

before singularity

Entrained air

Air entrainment

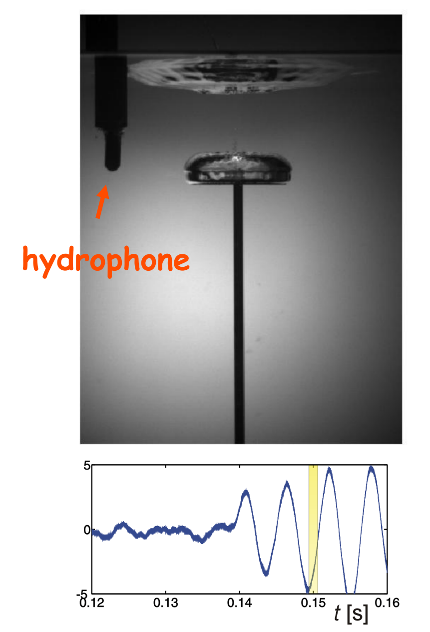


Strong tools to look at such questions as air entrainment

Profile of void just before singularity

Differences liquid vs soft sand

The sound of impact



t = 0.13 s

t = 0.14 s

t = 0.15 s

Minnaert formula:

$$f_r = \frac{1}{2\pi R_0}\sqrt{\frac{3\gamma P_0}{\rho_0}}$$

$f_r \approx 175$ Hz

⇕

$R_0 \approx 2.0$ cm

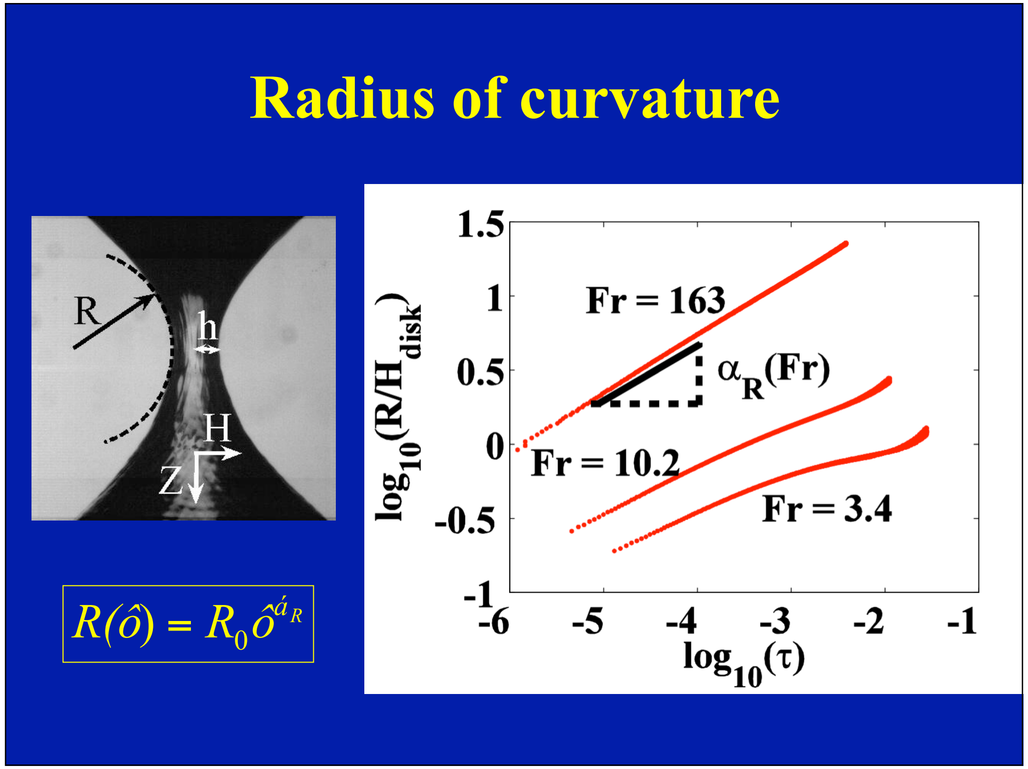
nb gamma = adiabatic exponent

Preparation of sand in our experiments

- Grain size = 40μm
- Let air bubble through it
- Slowly turn off air stream
- Resulting packing density: only 41%!

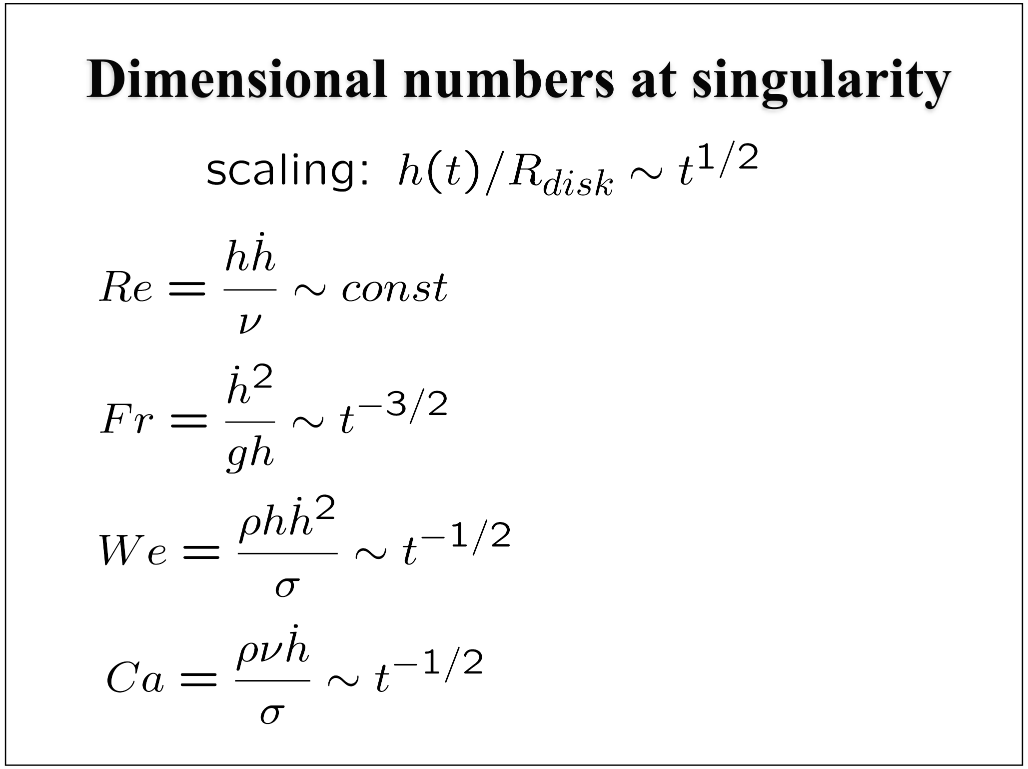
→ Model system for sedimented fine sand in the desert after a sand storm

Radius of curvature



$$R(\tau) = R_0\tau^{\alpha_R}$$

Include correction, but nevertheless at low froude there’s a significant deviation. The observed anomalous powerlaw of the neck radius must reflect itself in the in time evolution of the void. Define R, R exp increasing with froude



Dimensional numbers at singularity

scaling: $h(t)/R_{disk} \sim t^{1/2}$

$$Re = \frac{h\dot{h}}{\nu} \sim const$$

$$Fr = \frac{\dot{h}^2}{gh} \sim t^{-3/2}$$

$$We = \frac{\rho h\dot{h}^2}{\sigma} \sim t^{-1/2}$$

$$Ca = \frac{\rho\nu\dot{h}}{\sigma} \sim t^{-1/2}$$

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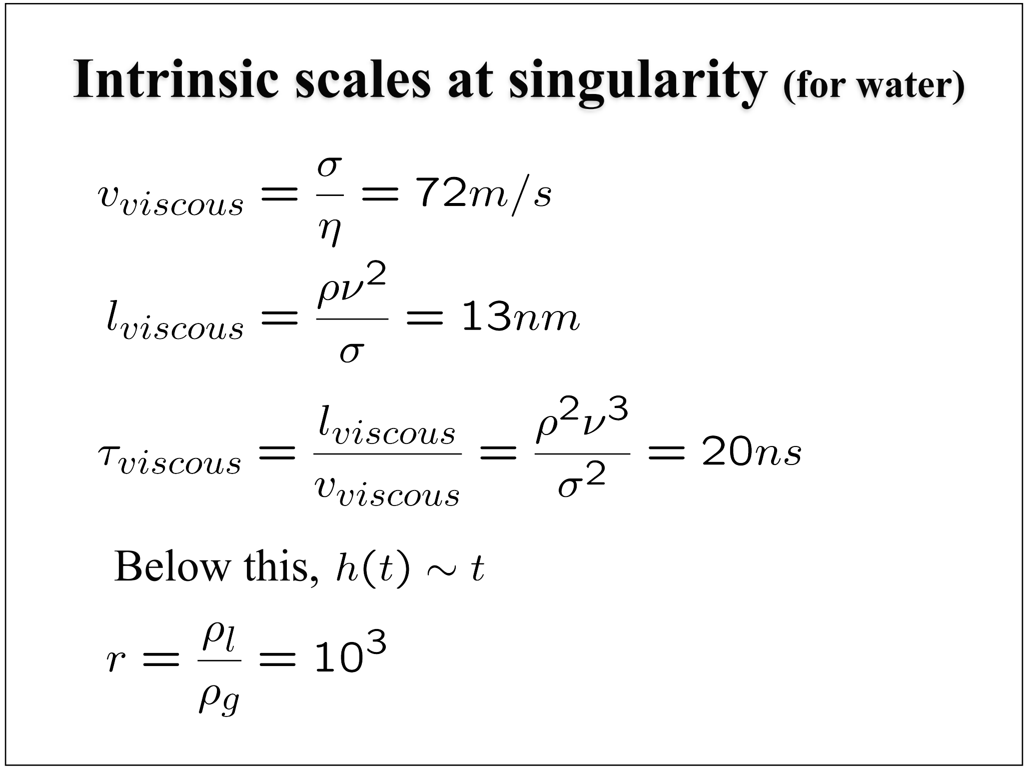

Intrinsic scales at singularity (for water)

$$v_{viscous} = \frac{\sigma}{\eta} = 72 m/s$$

$$l_{viscous} = \frac{\rho\nu^2}{\sigma} = 13 nm$$

$$\tau_{viscous} = \frac{l_{viscous}}{v_{viscous}} = \frac{\rho^2\nu^3}{\sigma^2} = 20 ns$$

Below this, $h(t) \sim t$

$$r = \frac{\rho_l}{\rho_g} = 10^3$$

I'M NOT AT ALL SURE ABOUT THE EQUALITY. CHECK MCMAHON & GLASHEEN FOR THEIR DEFINITION OF <v>!!!!!!

Intrinsic scales at singularity (for glycerol)

$$\nu_{glycerol} = 1000\nu_{water}$$

$$v_{viscous} = \frac{\sigma}{\eta} = 0.07 m/s$$

$$l_{viscous} = \frac{\rho\nu^2}{\sigma} = 13 mm$$

$$\tau_{viscous} = \frac{l_{viscous}}{v_{viscous}} = \frac{\rho^2\nu^3}{\sigma^2} = 20 s$$

Below this, $h(t) \sim t$

I'M NOT AT ALL SURE ABOUT THE EQUALITY. CHECK MCMAHON & GLASHEEN FOR THEIR DEFINITION OF <v>!!!!!!

Complete 2D-Rayleigh equation

$$(h\ddot{h} + \dot{h}^2)\log\frac{h}{h_\infty} + \tfrac{1}{2}\dot{h}^2 = gd_s + 2\nu\frac{\dot{h}}{h} + \frac{\sigma}{\rho h}$$

Viscous ~ capillary: $h(t) \sim t^1$

Viscous ~ inertia: $h(t) \sim t^{1/2}$

Inertia ~ capillary: $h(t) \sim t^{2/3}$

Purely inertially: $h(t) \sim t^{1/2}$

I'M NOT AT ALL SURE ABOUT THE EQUALITY. CHECK MCMAHON & GLASHEEN FOR THEIR DEFINITION OF <v>!!!!!!