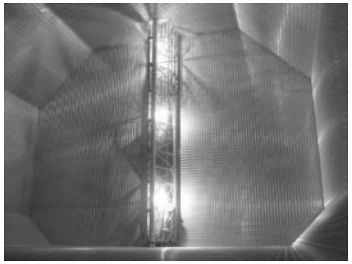
Expert in LNG

Experimental study of surface tension effects on sloshing impact loads

M. Frihat, L. Brosset and J.-M. Ghidaglia







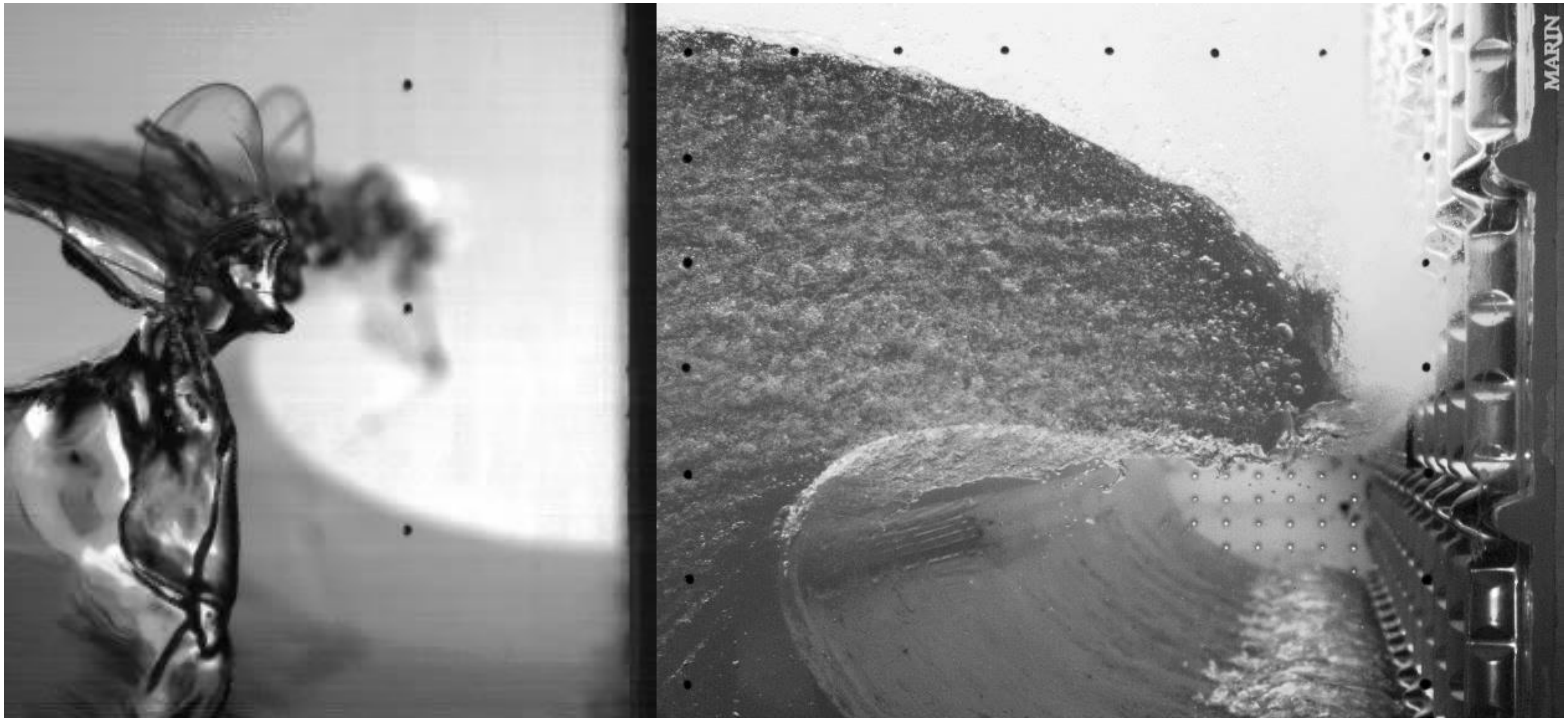
17th International Workshop on Trends in Numerical and Physical Modeling for Industrial Multiphase Flows

October 16 - 18, 2017- ENS Paris-Saclay, Cachan (France)

Safety | Excellence | Innovation | Teamwork | Transparency

Free surface instabilities generated by the shearing gas flow during liquid impacts

- Free surface instabilities: *Kelvin-Helmholtz, Plateau-Rayleigh ?*



Scale 1:6 **Scale 1:1**

Sloshel JIP led by MARIN

Weber and Reynolds similarity: ideal scaling of surface tension and kinematic viscosity

Weber similarity

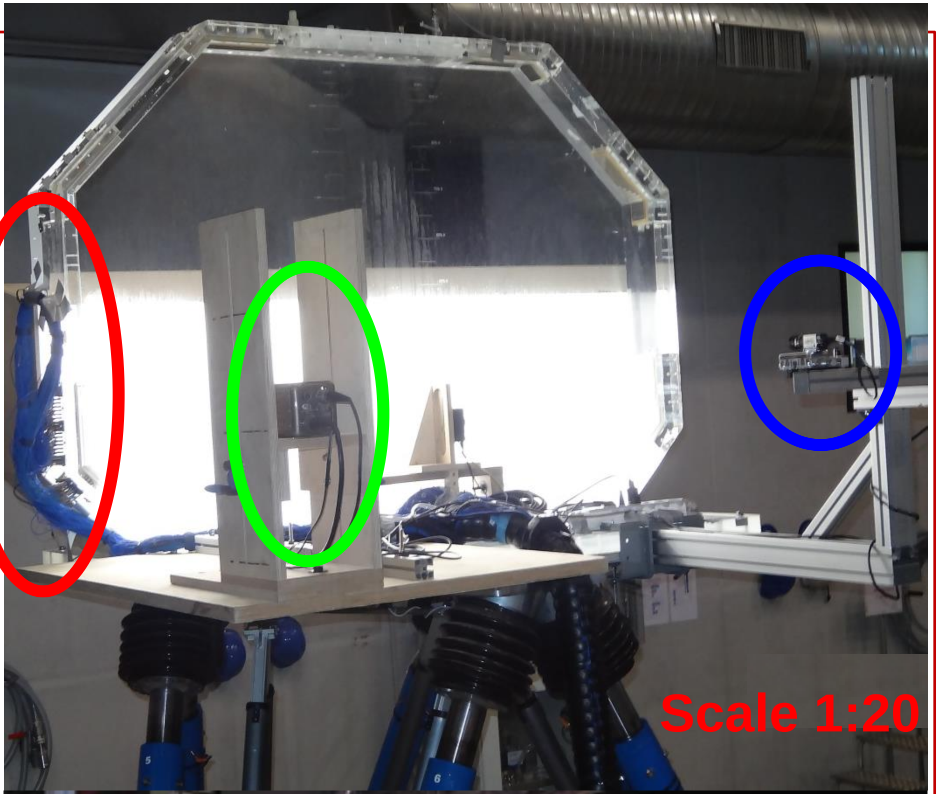
- $\rho_l^{[\frac{1}{\lambda}]} \frac{L_0^{[\frac{1}{\lambda}]}\left[U_l^{[\frac{1}{\lambda}]}\right]^2}{\sigma^{[\frac{1}{\lambda}]}} = \rho_l^{[1]} \frac{L_0^{[1]}\left[U_l^{[1]}\right]^2}{\sigma^{[1]}}$ → $\sigma^{[\frac{1}{\lambda}]} = \frac{\sigma^{[1]}}{\mu\lambda^2}$
- For λ=40 and μ=0.5 → $\sigma^{[\frac{1}{40}]} = \frac{\sigma^{[1]}}{800}$

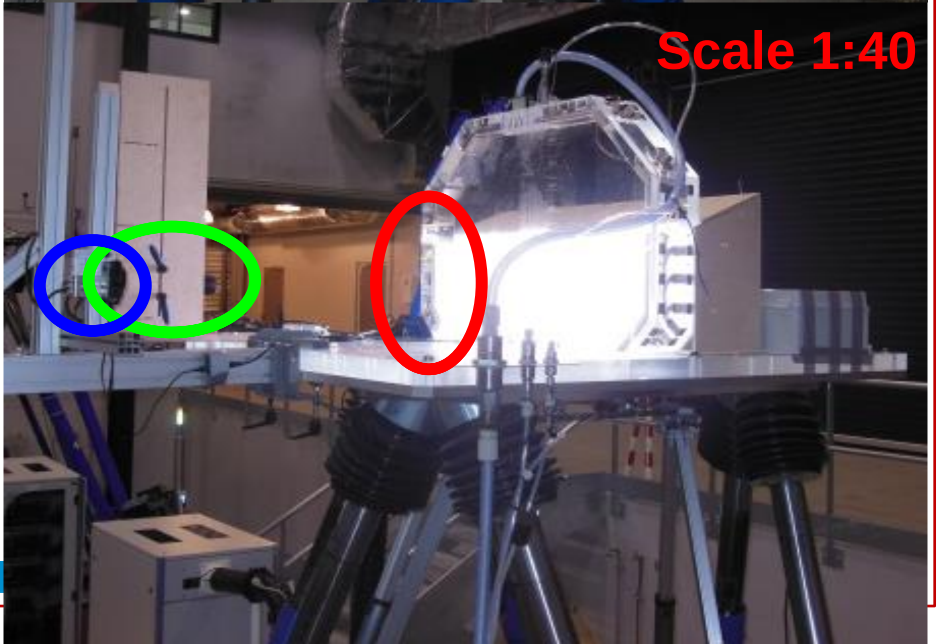
Reynolds similarity for L & G

- $R_k = \frac{U_k^{[\frac{1}{\lambda}]} L_0^{[\frac{1}{\lambda}]}}{\nu_k^{[\frac{1}{\lambda}]}} = \frac{U_k^{[1]} L_0^{[1]}}{\nu_k^{[1]}}$ → $\nu_k^{[\frac{1}{\lambda}]} = \frac{\nu_k^{[1]}}{\lambda^{\frac{3}{2}}}$ k=l or g
- For λ=40 → $\nu_k^{[\frac{1}{40}]} = \frac{\nu_k^{[1]}}{253}$

Test Setups

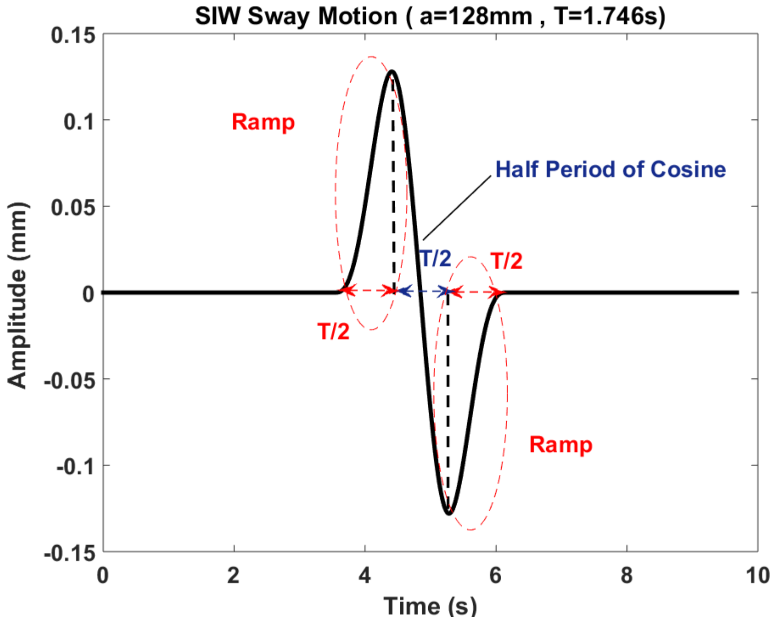
- **2D tank @ Scale 1:20 & 1:40**
  - Transverse slice of a real tank
  - 152 000 m^3 LNG carrier
- **Hexapod (6 ddl)**
- **PCB pressure sensors (piezo)**
  - 40 kHz
- **High-speed camera**
  - 4000 fps
- **Semi high-speed video camera**
  - 100 fps
- **Different solutions of Water and Air**
  - 20%H





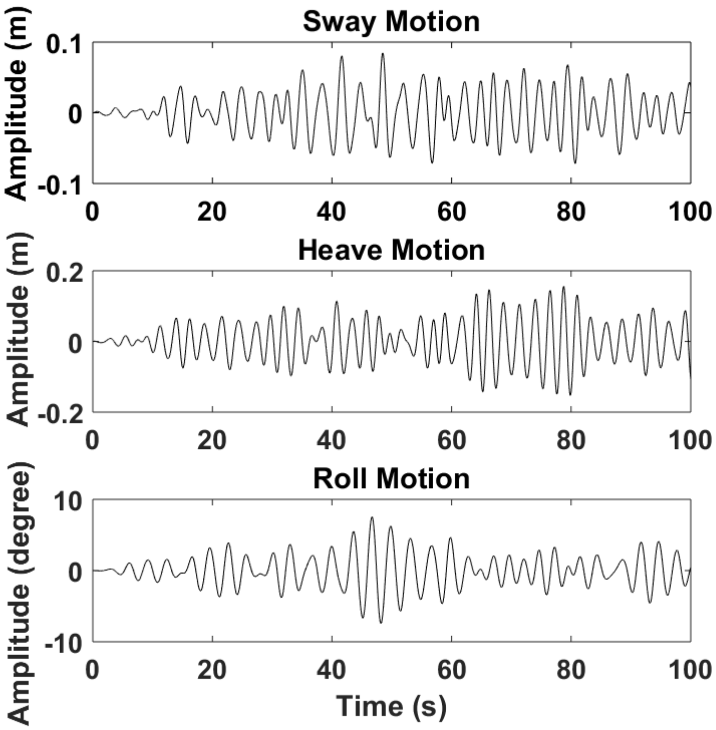
Two types of forced motions

- **Single Impact Waves (SIW)**



- Sway motion starting from rest
- Short duration
- Only the first impact is studied

- **Irregular motions**

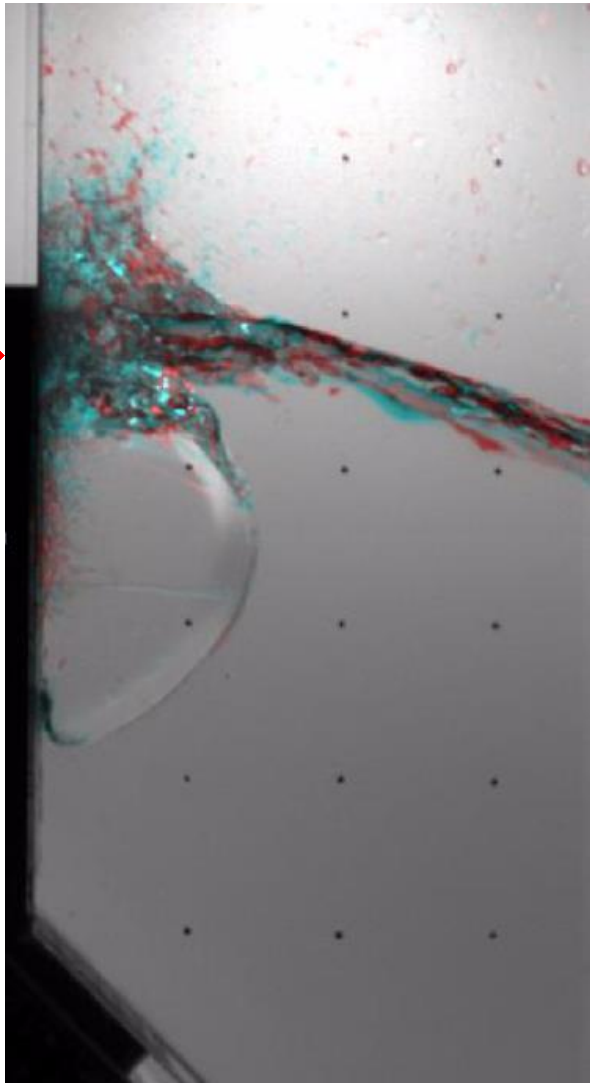


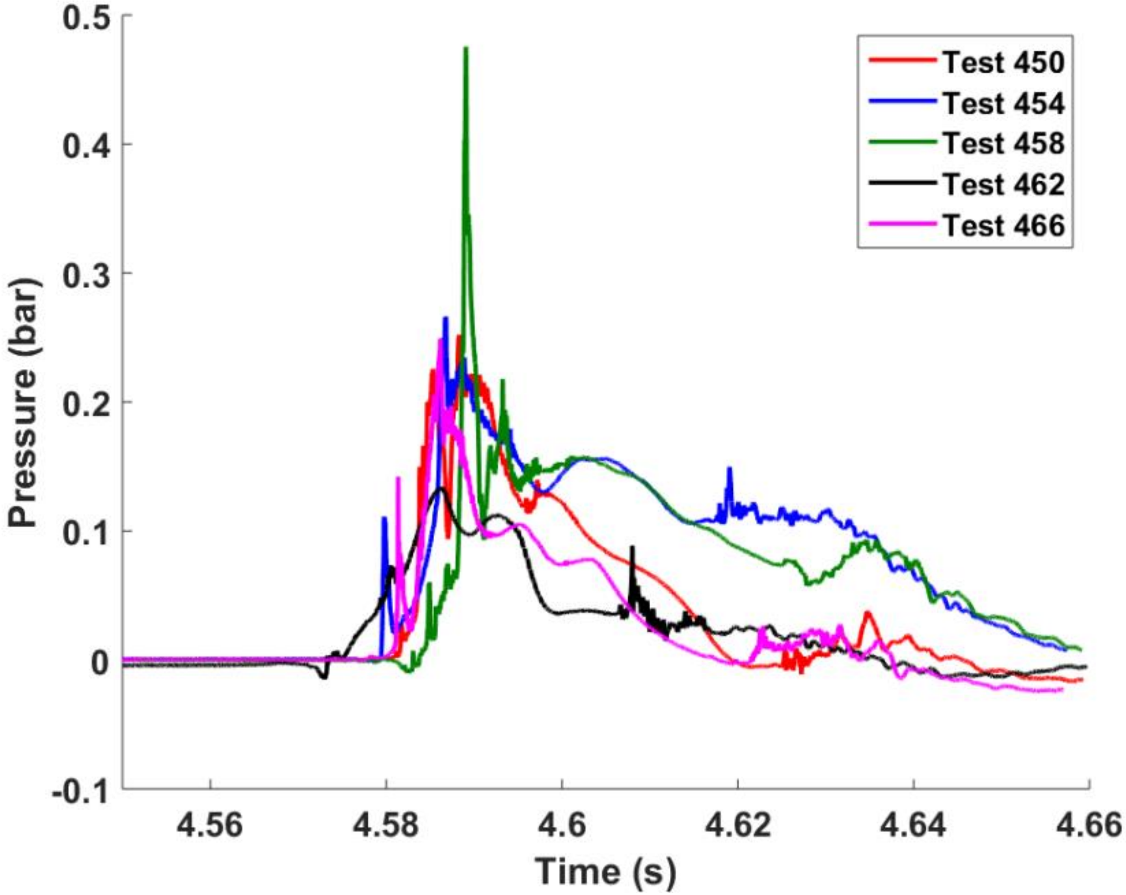
- Calculations of ship motions at scale 1
- Down-scaling by Froude
- Only the 3 dof in the plane of the tank
- 5-hours @ full scale

Weber and Reynolds similarity: ideal scaling of surface tension and kinematic viscosity

- **Weber similarity**
  - $\rho_l^{[\frac{1}{\lambda}]} \frac{L_0^{[\frac{1}{\lambda}]} \left[U_l^{[\frac{1}{\lambda}]}\right]^2}{\sigma^{[\frac{1}{\lambda}]}} = \rho_l^{[1]} \frac{L_0^{[1]} \left[U_l^{[1]}\right]^2}{\sigma^{[1]}}$ → $\sigma^{[\frac{1}{\lambda}]} = \frac{\sigma^{[1]}}{\mu\lambda^2}$
  - For λ=40 and μ=0.5 → $\sigma^{[\frac{1}{40}]} = \frac{\sigma^{[1]}}{800}$
  - For λ=2 and μ=1 → $\sigma^{[\frac{1}{40}]} = \frac{\sigma^{[\frac{1}{20}]}}{4}$
- **Reynolds similarity for L & G**
  - $R_k = \frac{U_k^{[\frac{1}{\lambda}]} L_0^{[\frac{1}{\lambda}]}}{\nu_k^{[\frac{1}{\lambda}]}} = \frac{U_k^{[1]} L_0^{[1]}}{\nu_k^{[1]}}$ → $\nu_g^{[\frac{1}{\lambda}]} = \frac{\nu_g^{[1]}}{\lambda^{\frac{3}{2}}}$
  - For λ=40 → $\nu_g^{[\frac{1}{40}]} = \frac{\nu_g^{[1]}}{253}$
  - For λ=2 → $\nu_g^{[\frac{1}{40}]} = \frac{\nu_g^{[\frac{1}{20}]}}{2.83}$

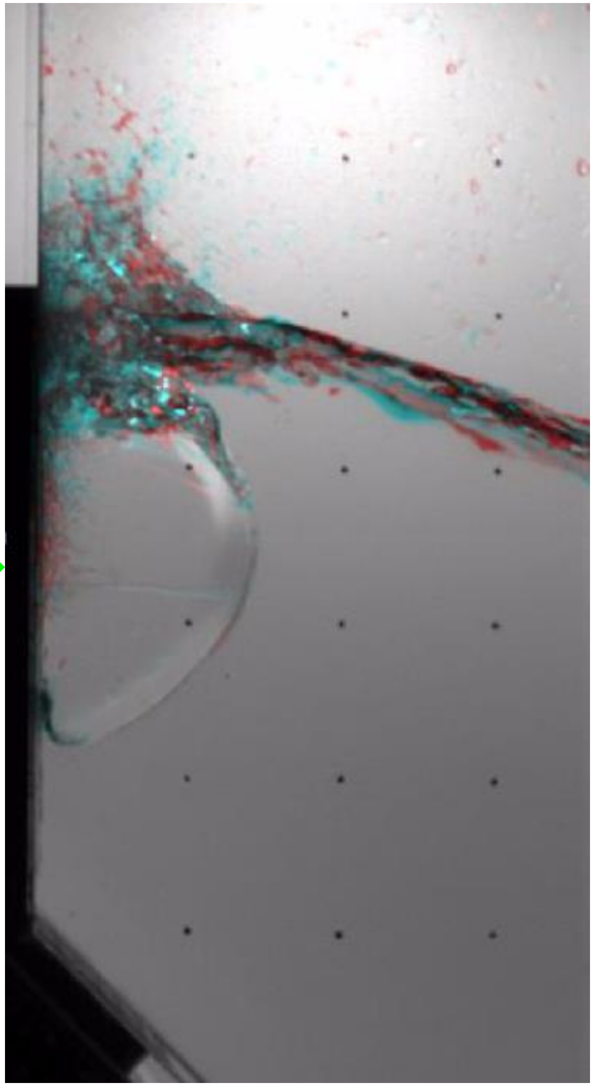
Pressure Variability and free surface instabilities

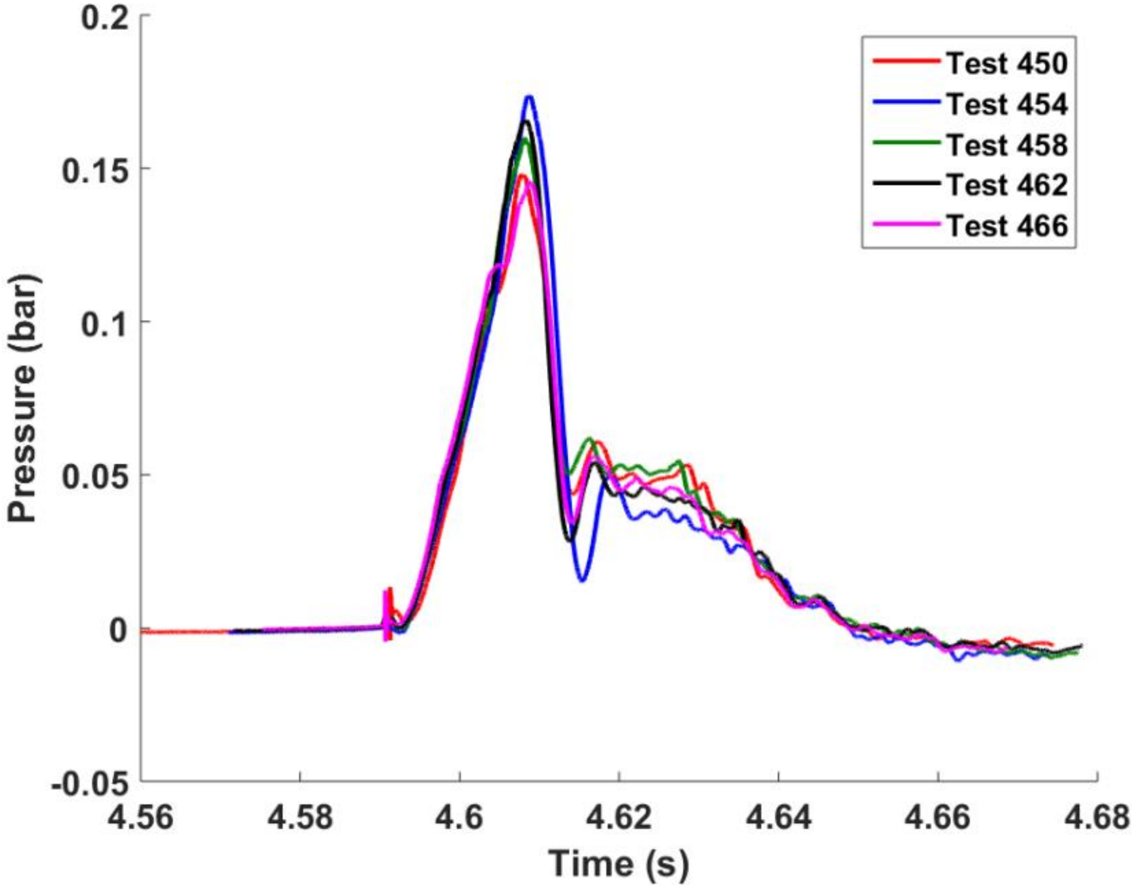




Large variability

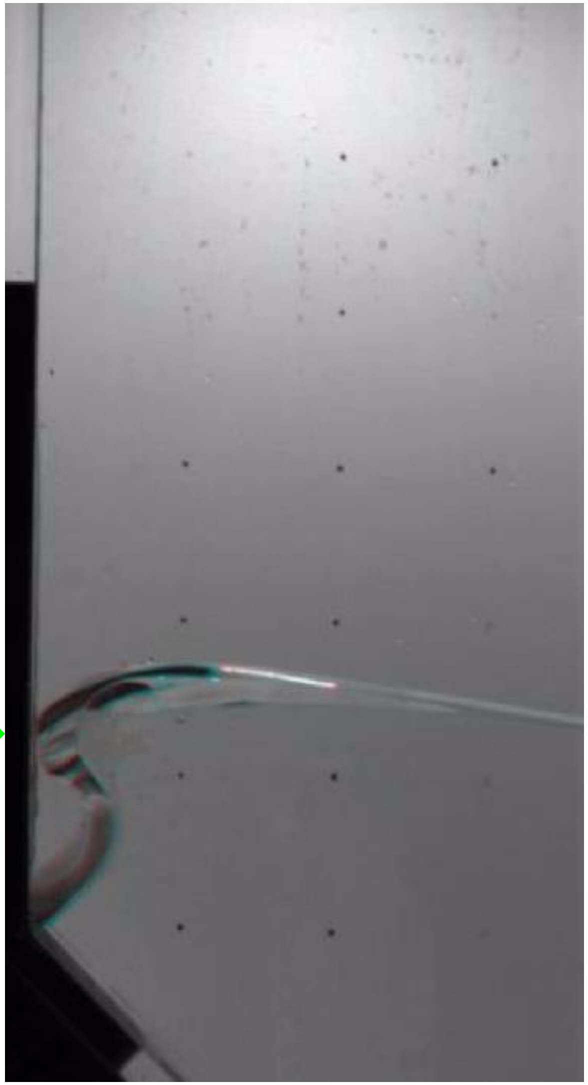
Pressure Variability and free surface instabilities

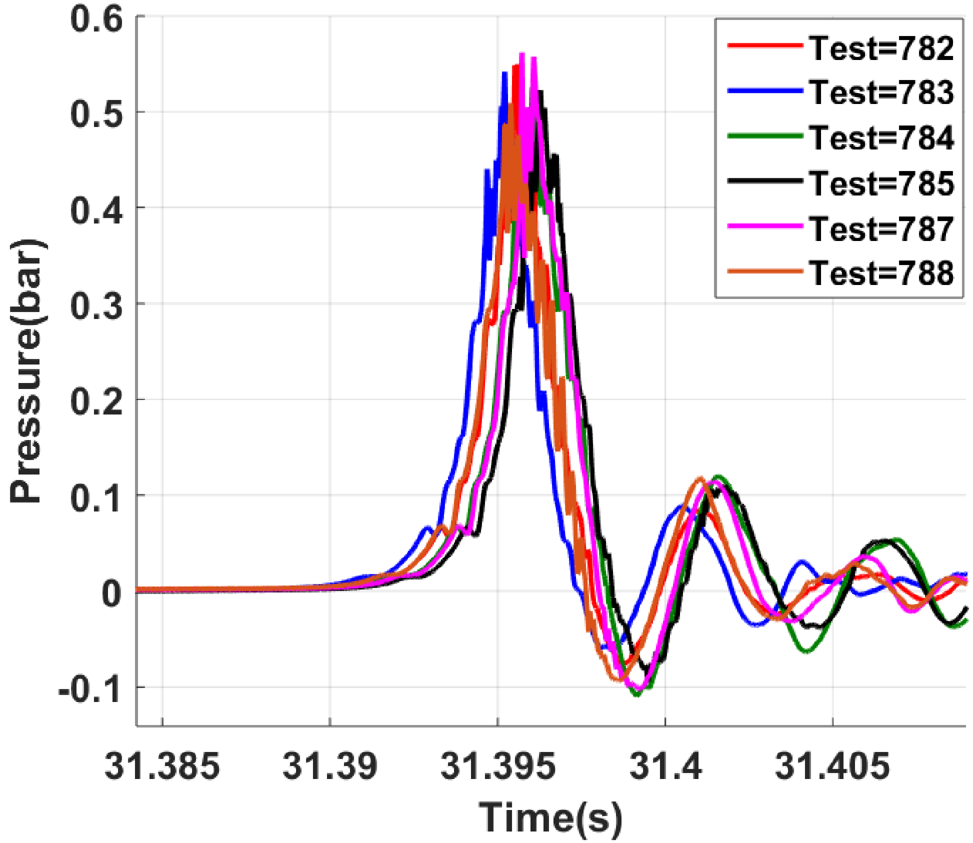




Good repeatability

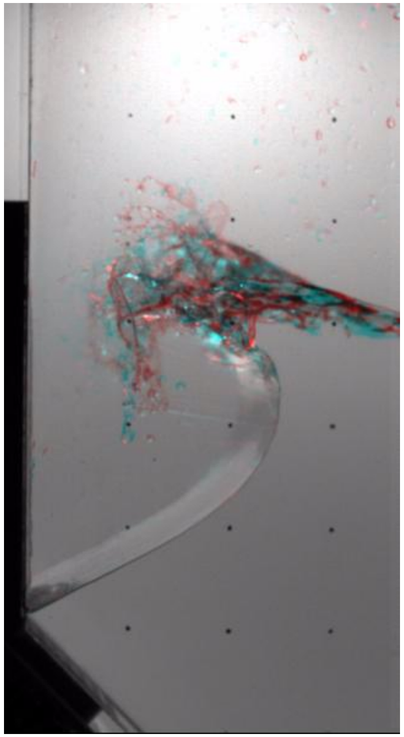
Pressure Variability and free surface instabilities

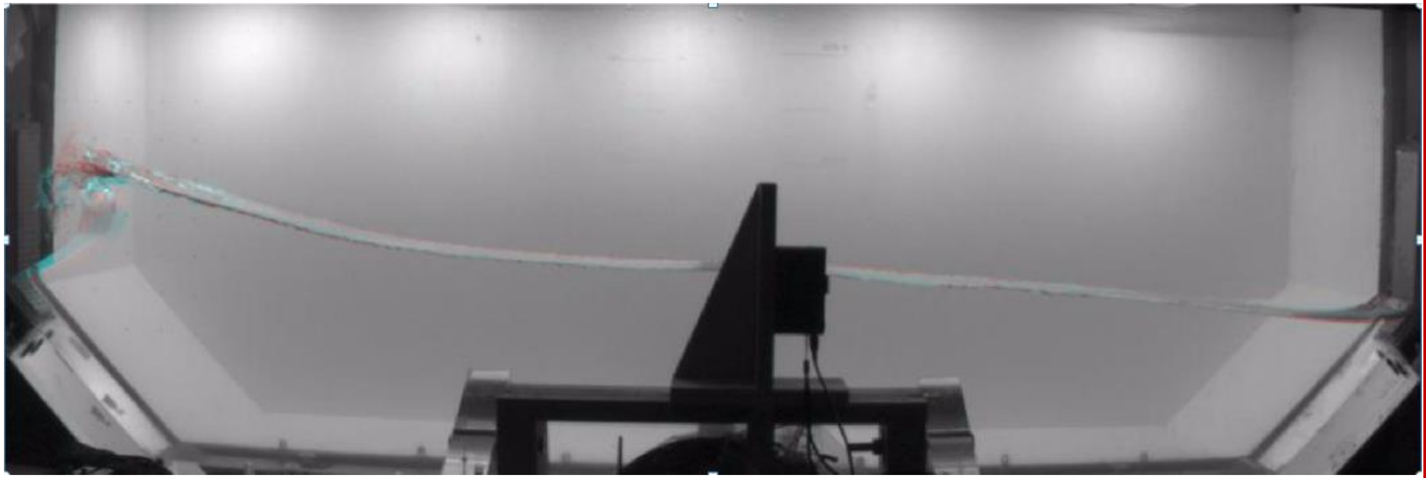




Good repeatability

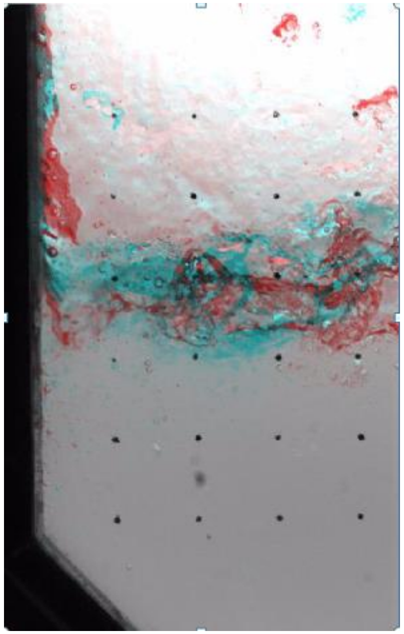
Sources of Variability: before the first impact

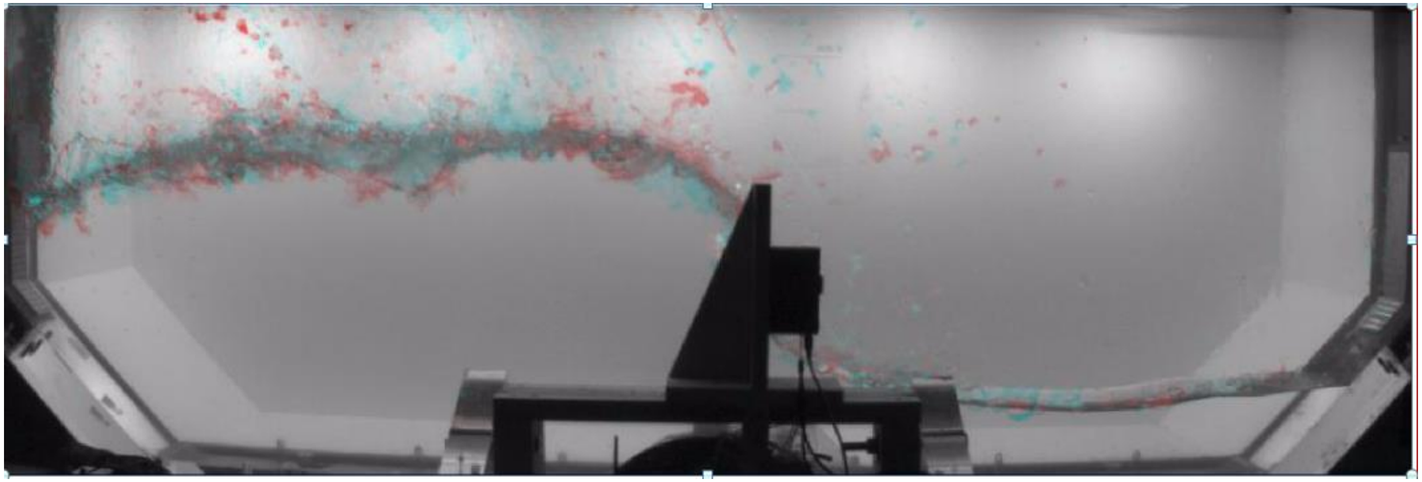




- Repetable global flow before the impact.
- Local variations due to the free surface instabilities.
- Production of bubbles during the impact.

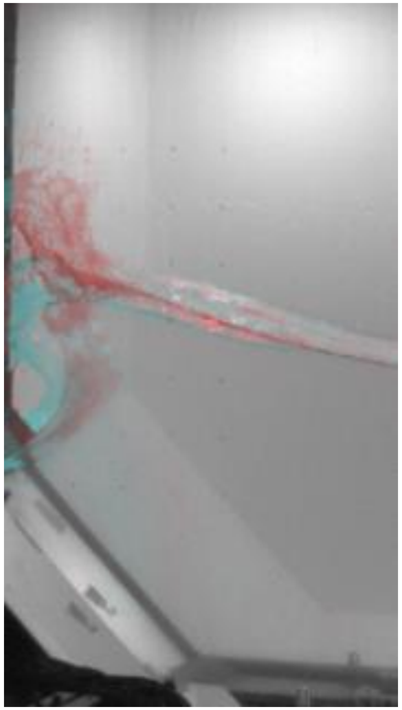
Sources of Variability: after the first impact

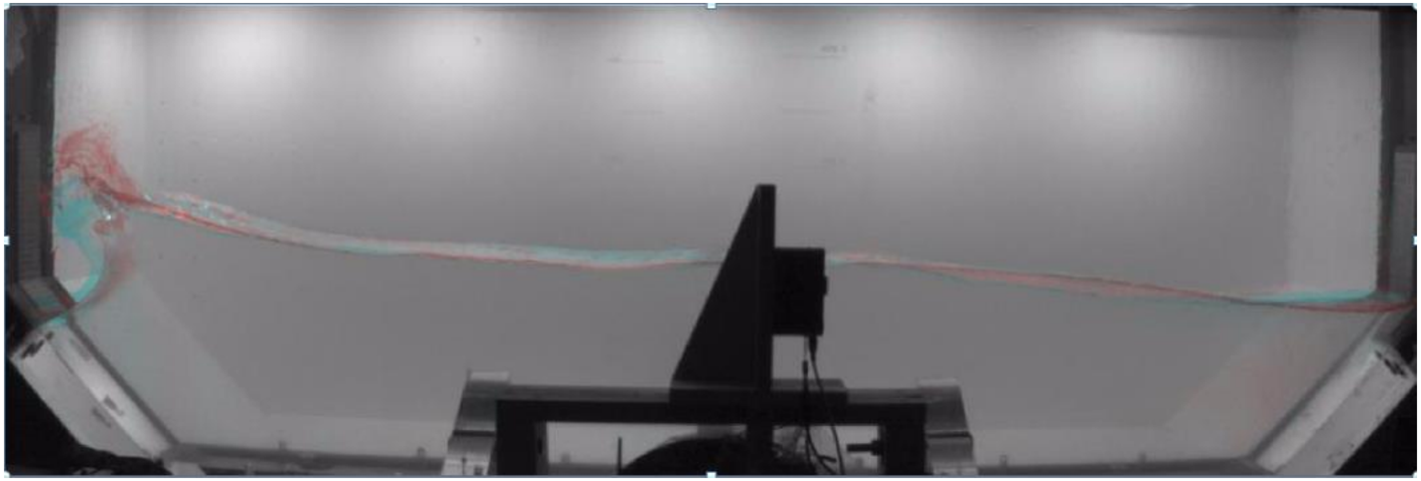




- Repetable global flow before the impact
- Local variations due to the free surface instabilities
- Production of bubbles during the impact
- **Fall of droplets after splashing**

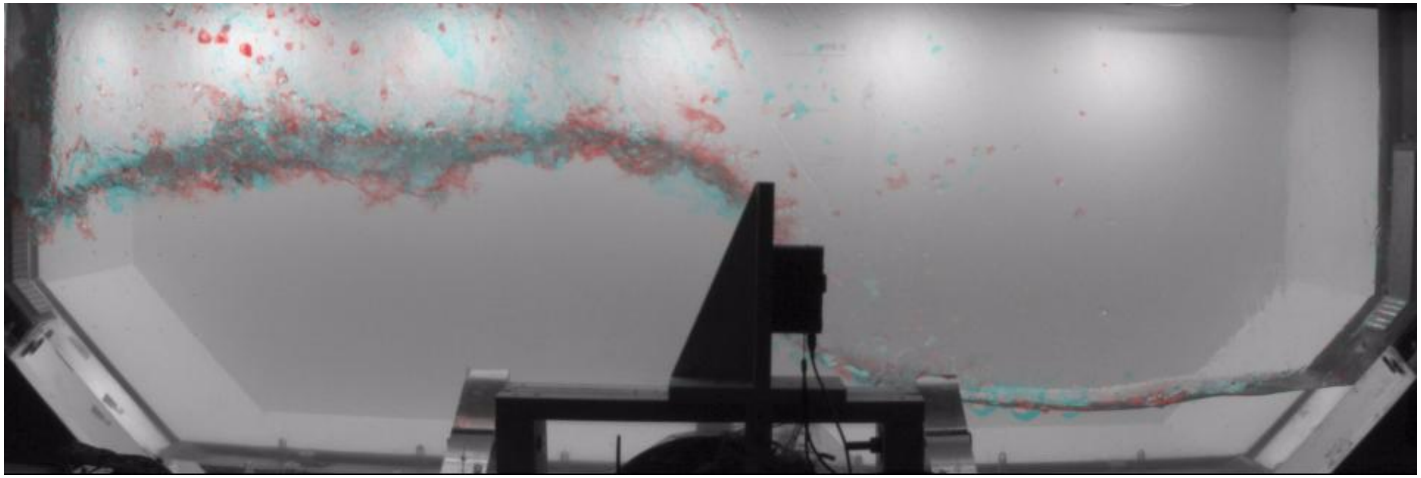
Sources of Variability: succession of impacts





- Repetable global flow before the impact
- Local variations due to the free surface instabilities
- Production of bubbles during the impact
- Fall of droplets after splashing
- **Variations of the global flow**

Flow regularization



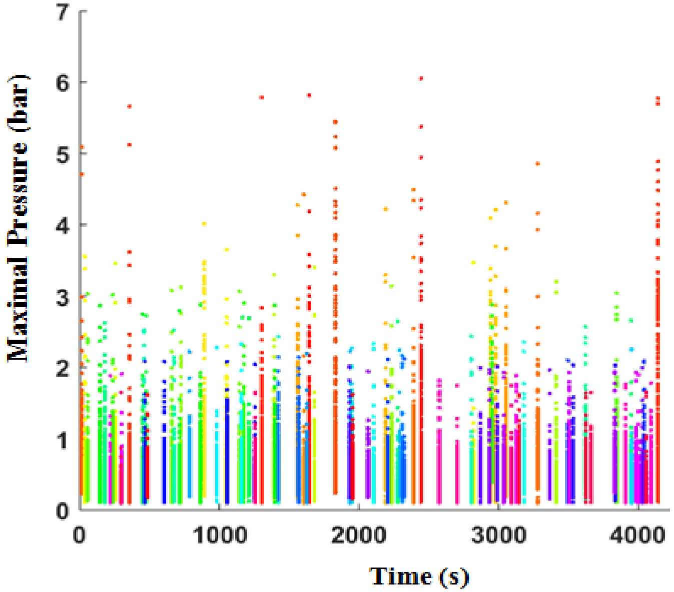
- Energy dissipation by viscous friction
- Flow regularization brought by forced motions

Balance between production of variability and flow regularization

- The flow remains in phase even after a long duration
- Impacts always happen at the same instants (considering a tolerance window of 50 ms)

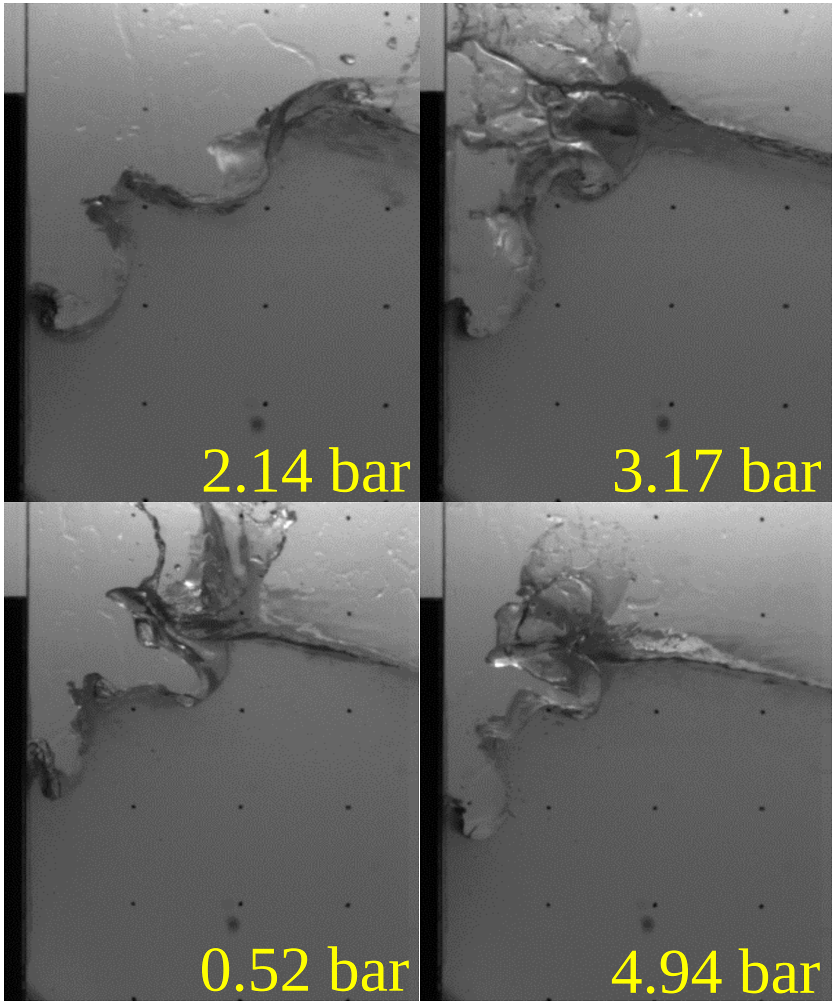
Irregular Motions Tz=8.5 s, Hs=6m

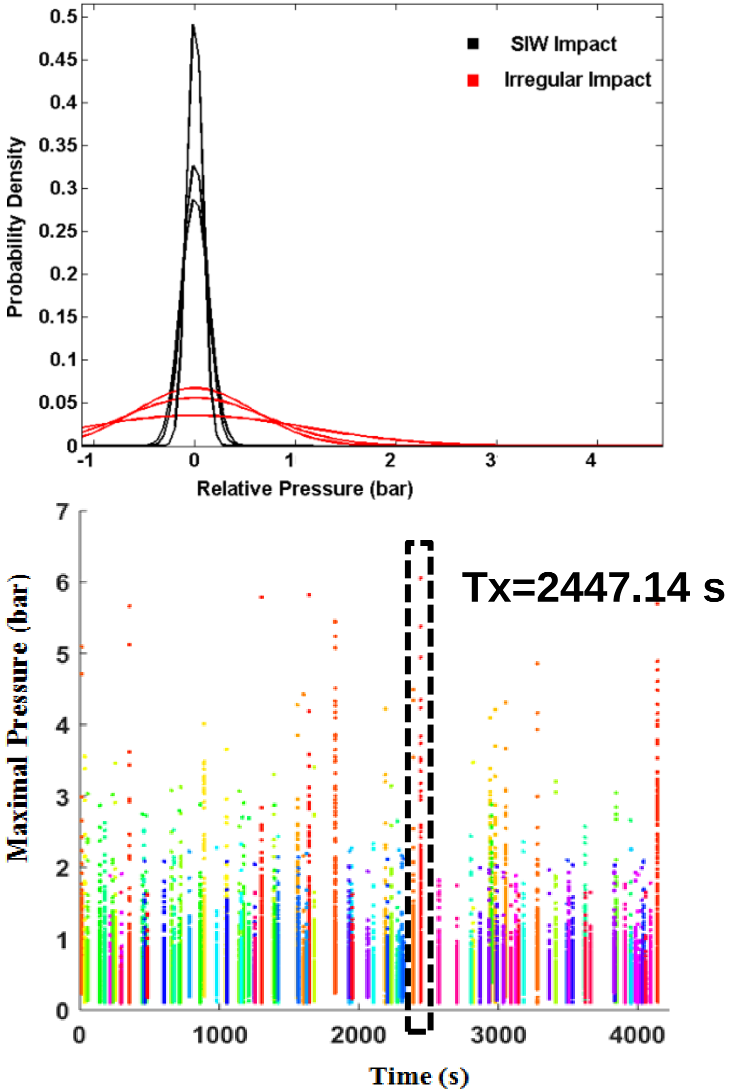
- There is a balance between production of variability and regularization which prevents the global flow to diverge
- The duration for the balance to be right can be considered as a flow memory



Coincident impacts after 200 repetitions

Impact coincidences





Coincident impacts after 200 repetitions

Aqueous solutions studied

▶ Properties of the different solutions studied

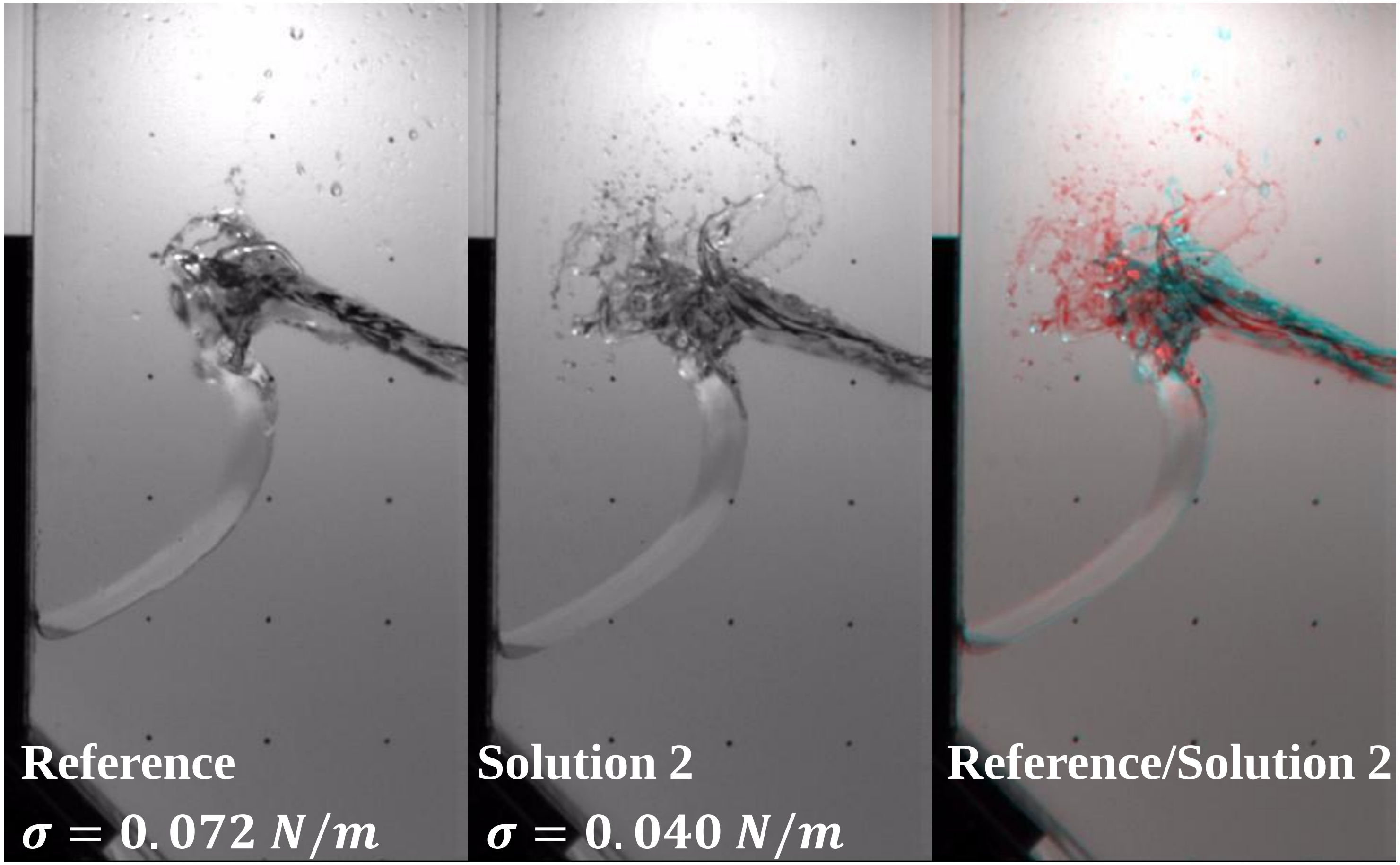
Name	Composition	Density (kg/m^3)	Surface tension (mN/m)	Dynamic Viscosity (mPa.s)	Speed of Sound (m/s)
Reference	Water	998	72	1	1500
Solution 1	Water + Ethanol	997	60	1 < …< 1.22	1500 < … < 1561
Solution 2	Water + Surfactant	998	40	1	1500
Solution 3	Water + Surfactant	998	35	1	1500
Solution 4	Water + Surfactant	998	30	1	1500
Solution 5	Water + Propanol-1	985	35	1 < …< 1.5	1500 < … < 1594
Solution 6	Water + Propanol-1	974	30	1 < …< 1.5	1594

Properties at 25° C

▶ Forced motions studied @ both scales

- 7 different Single Impact Waves
- 8 coincident impacts giving the highest pressures @ scale 1:20
- A complete irregular motion (5 hours @ full scale)

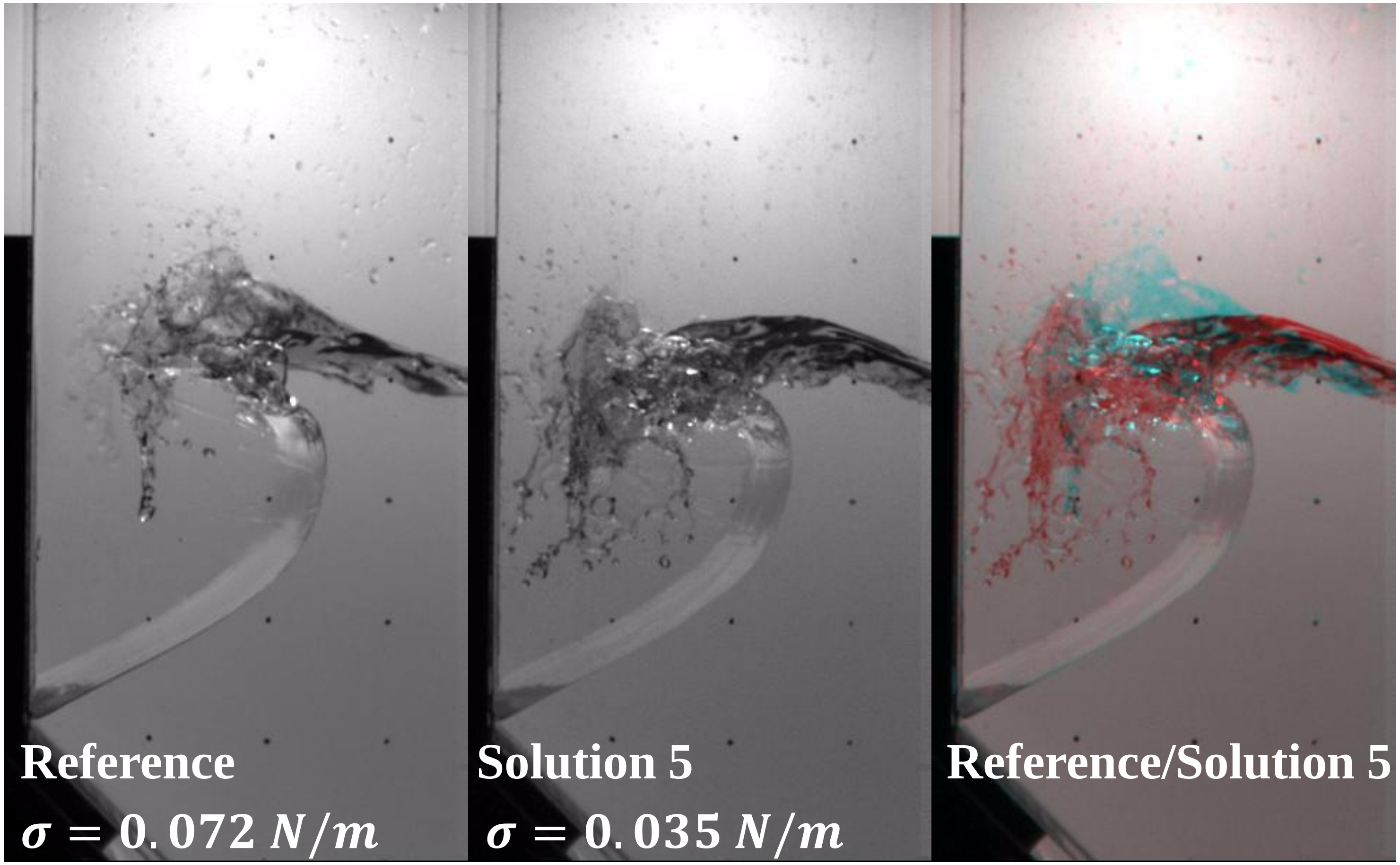
Effects of surface tension on Single Impact Waves at scale 1:20



SIW_1 : a = 236 mm, T = 2.47 s

Start/Stop

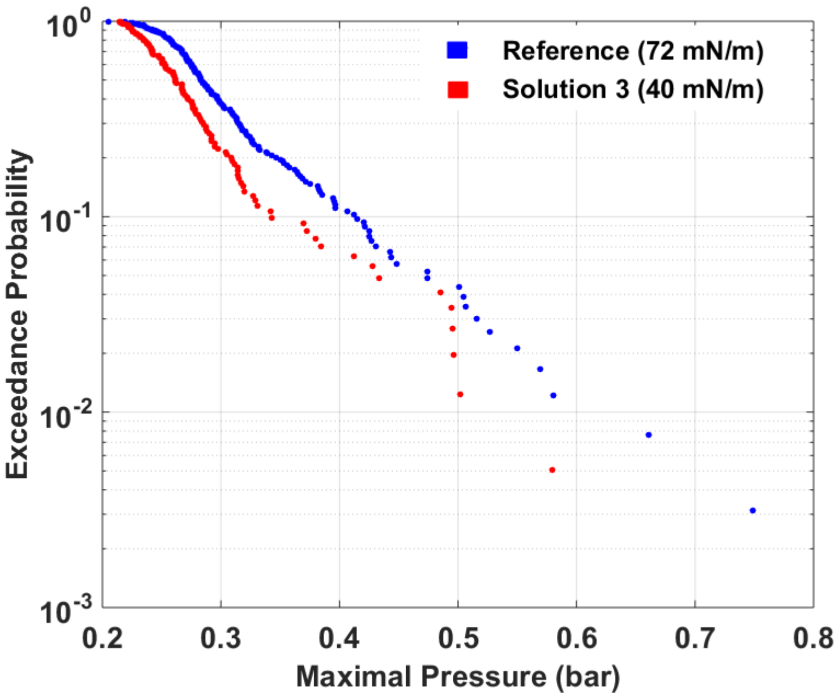
Effects of surface tension on Single Impact Waves at scale 1:20



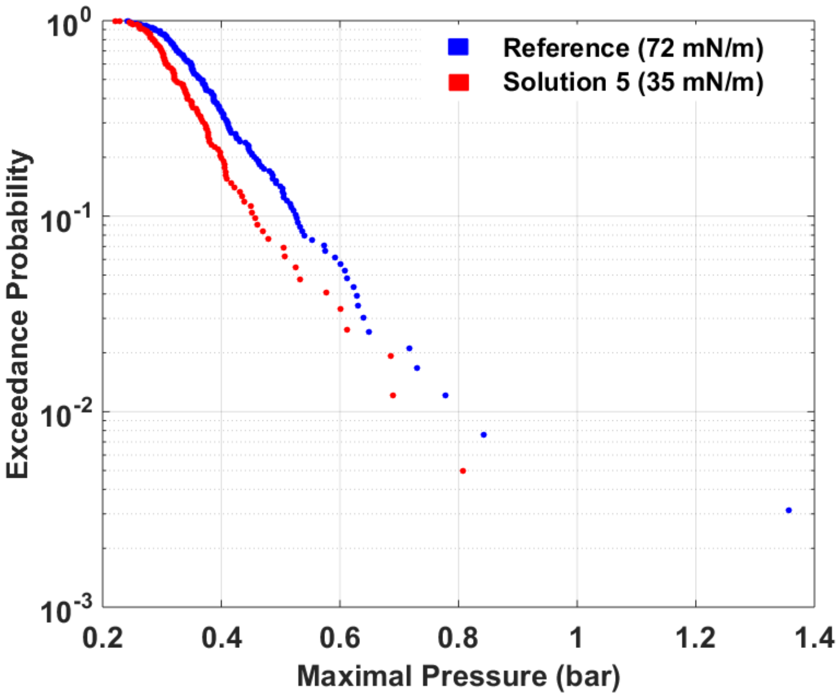
SIW_2 : a = 244 mm, T = 2.47 s

Start/Stop

Effects of surface tension on Single Impact Waves at scale 1:20

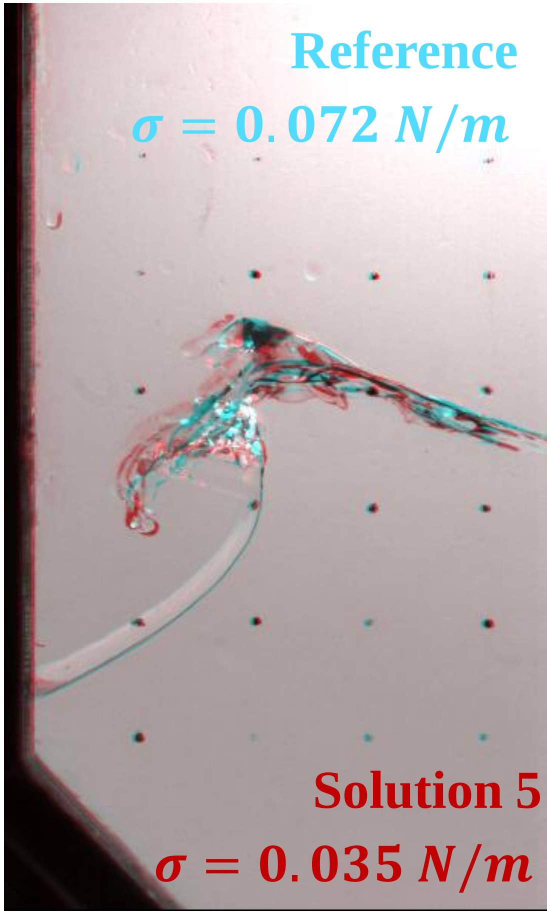


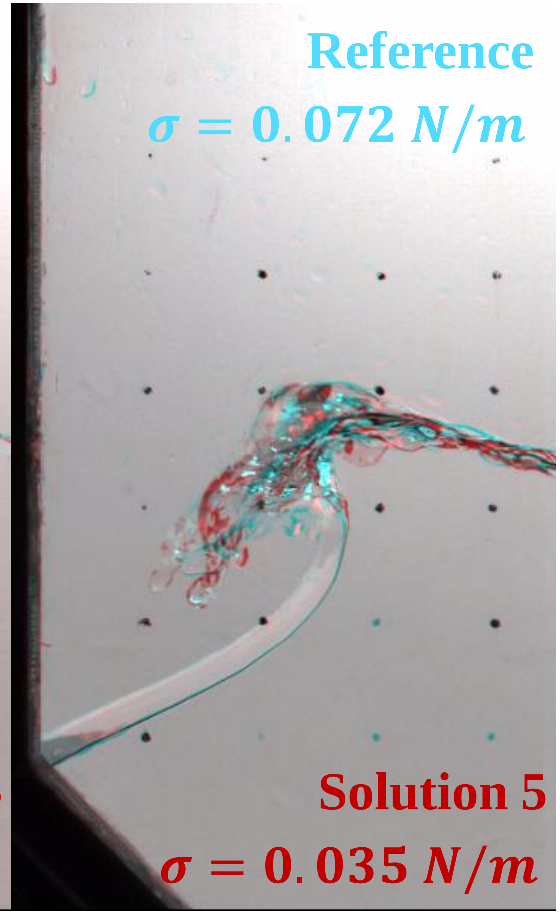
SIW_1 : a = 236 mm, T = 2.47 s



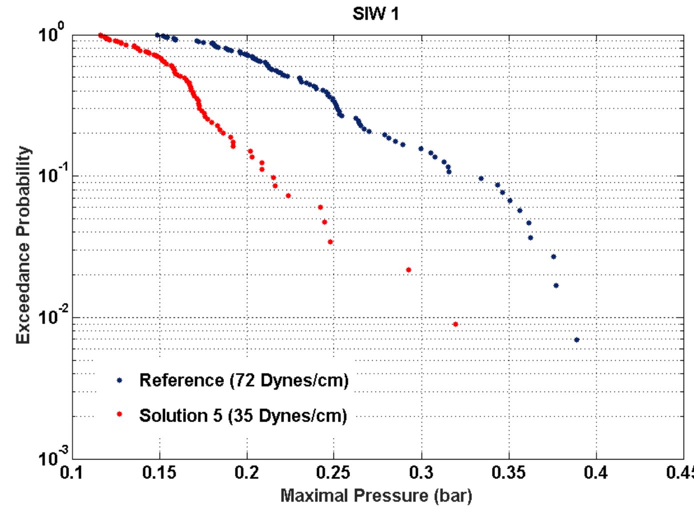
SIW_2 : a = 244 mm, T = 2.47 s

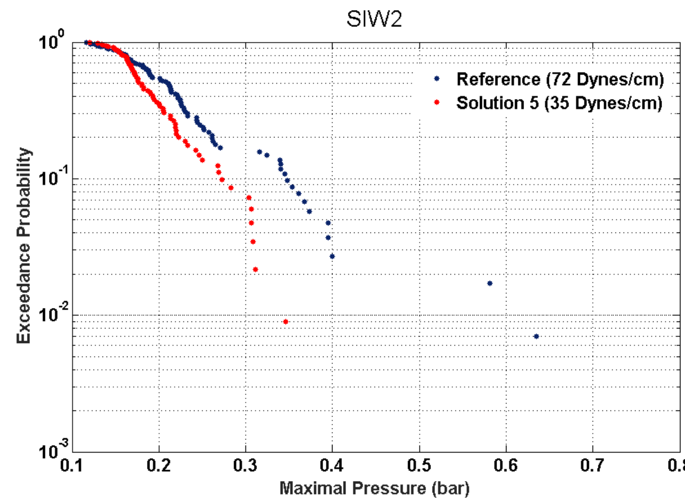
Effects of surface tension on Single Impact Waves at scale 1:40





SIW_1 : a = 118 mm **SIW_2 : a = 122 mm**





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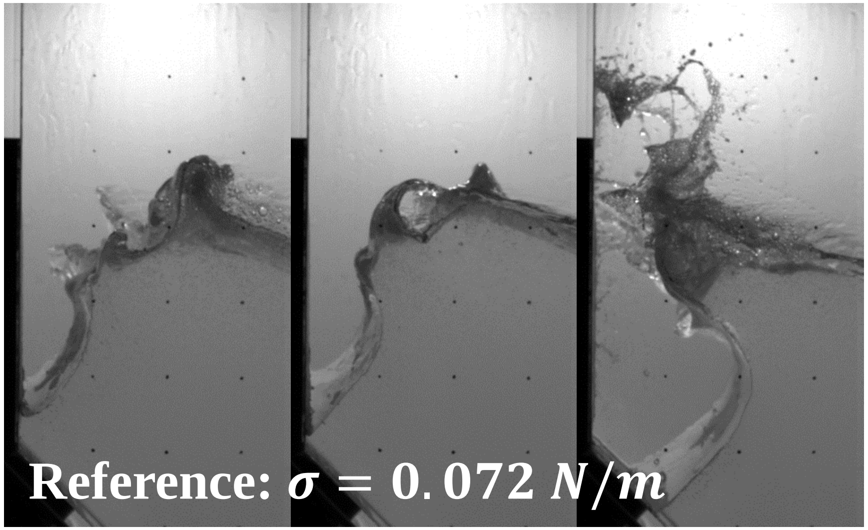
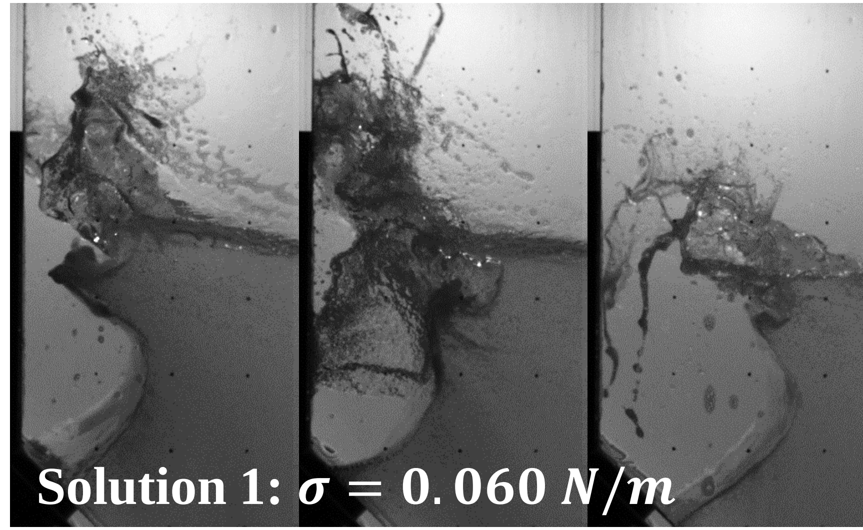
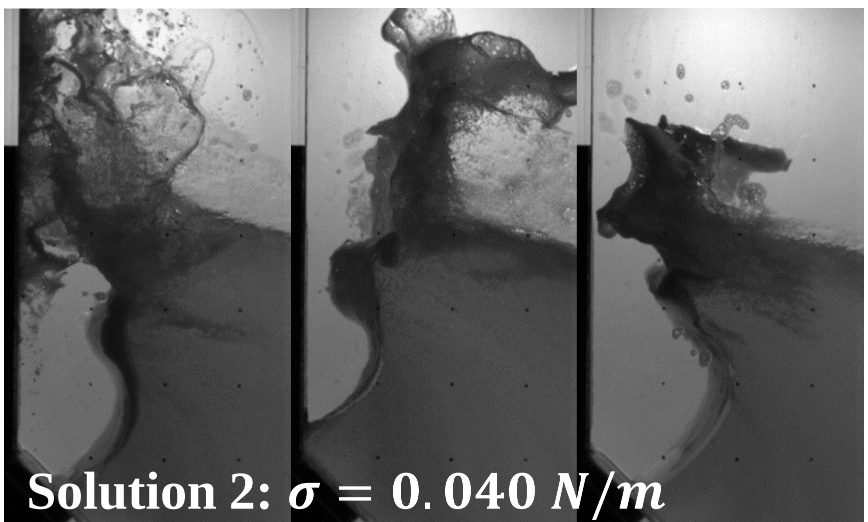
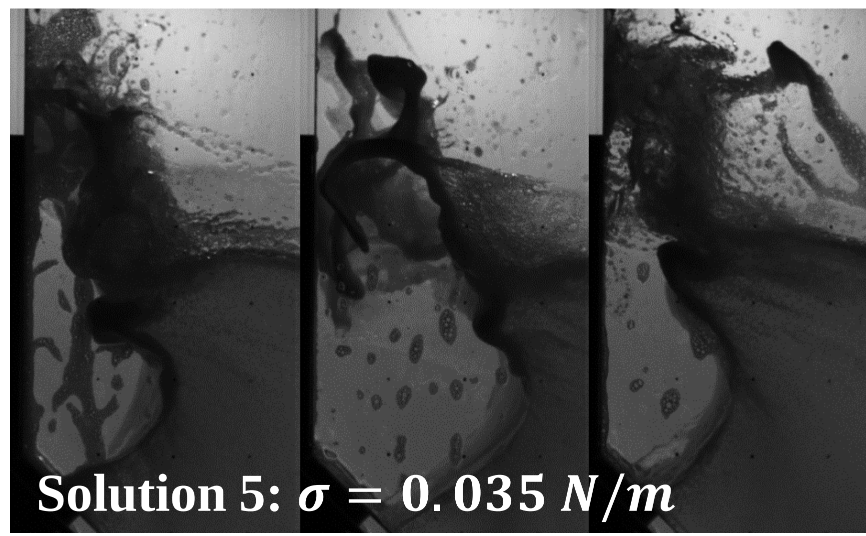
Effects of surface tension on Coincident Impacts at scale 1:20

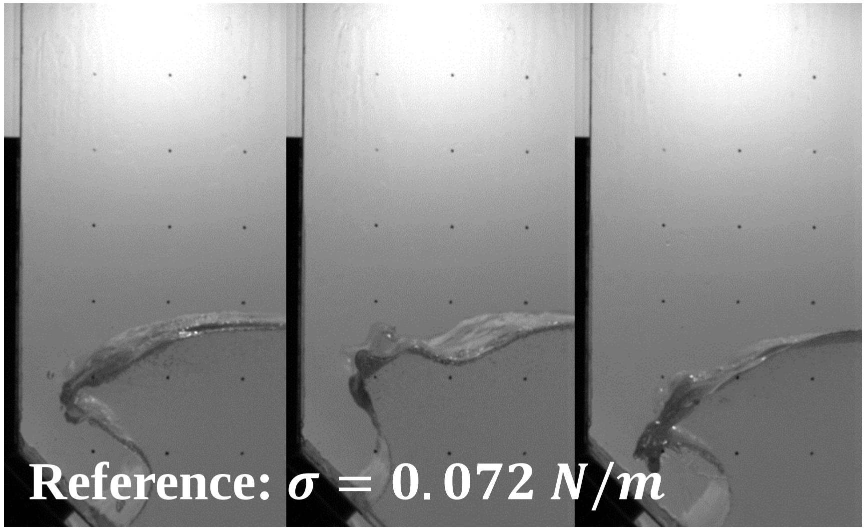


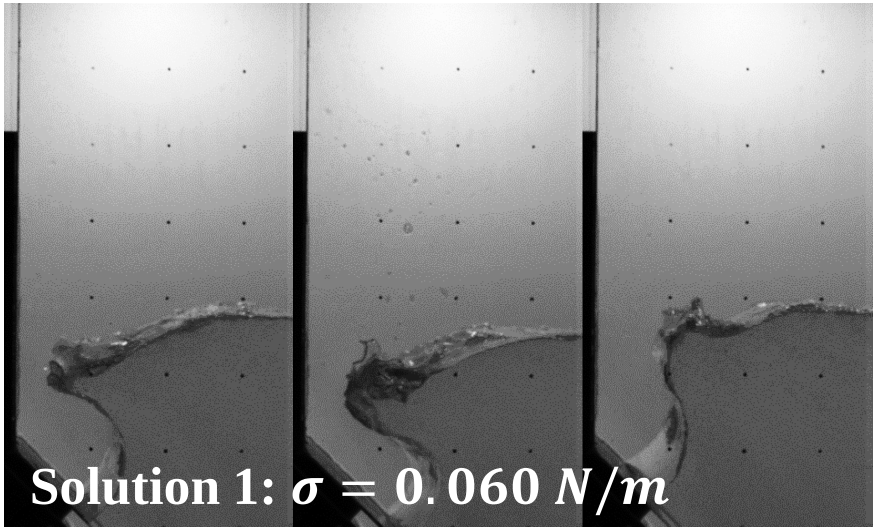


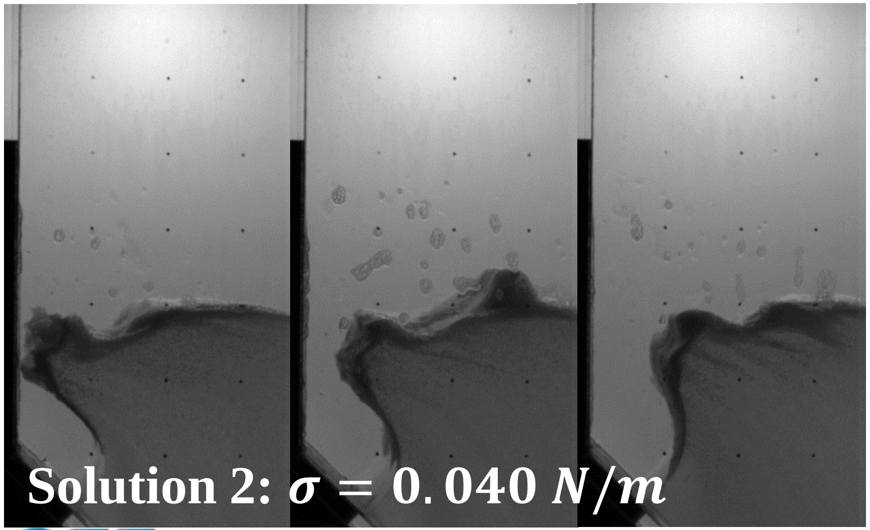


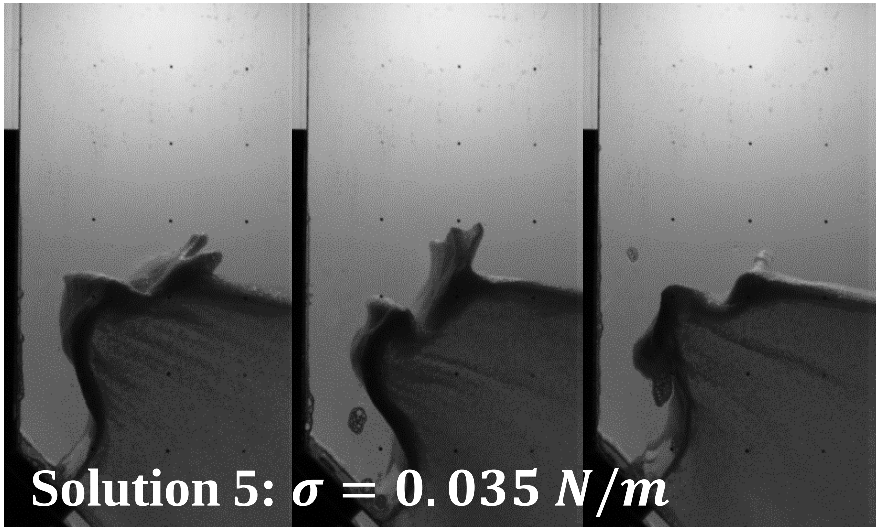


Effects of surface tension on Coincident Impacts at scale 1:20

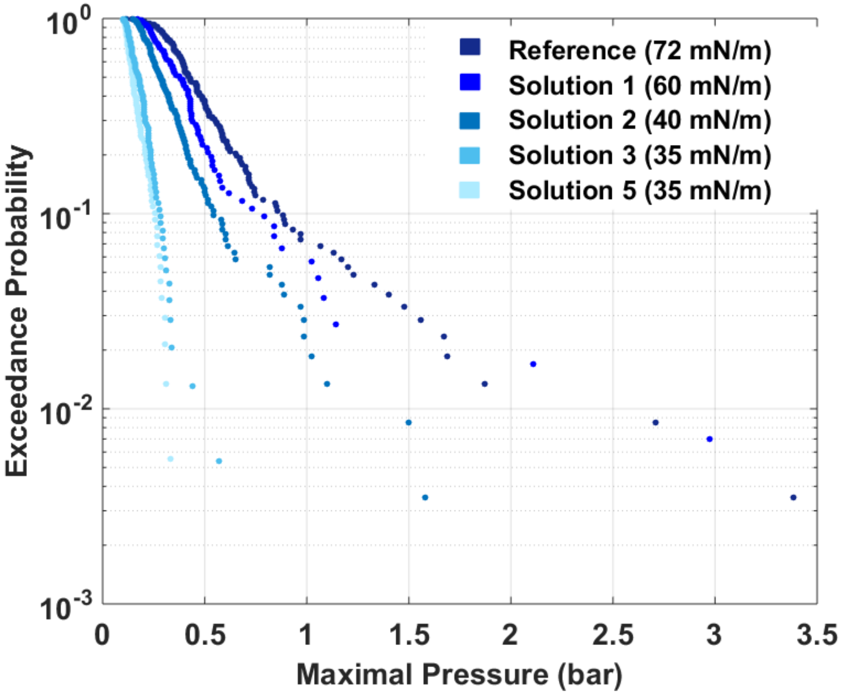




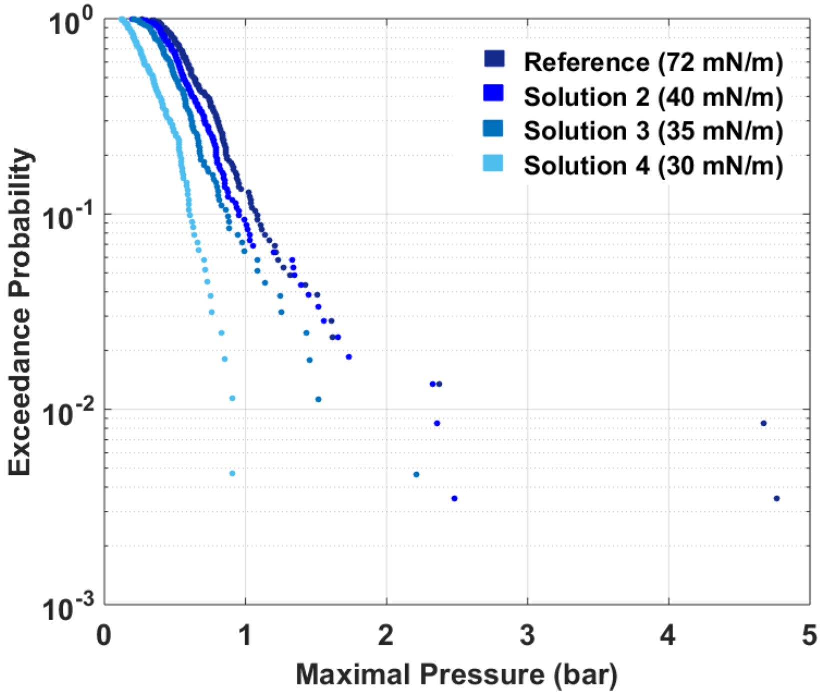




Effects of surface tension on Coincident Impacts at scale 1:20

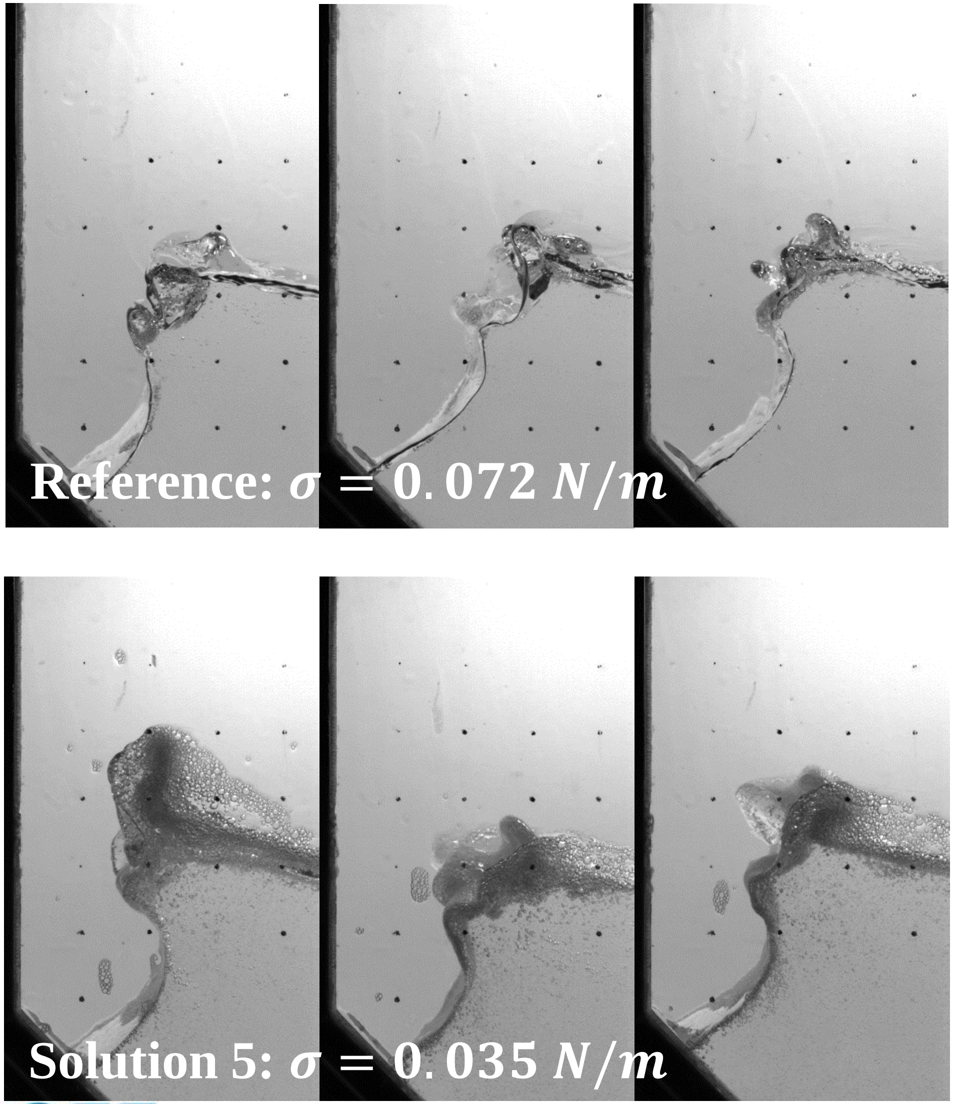


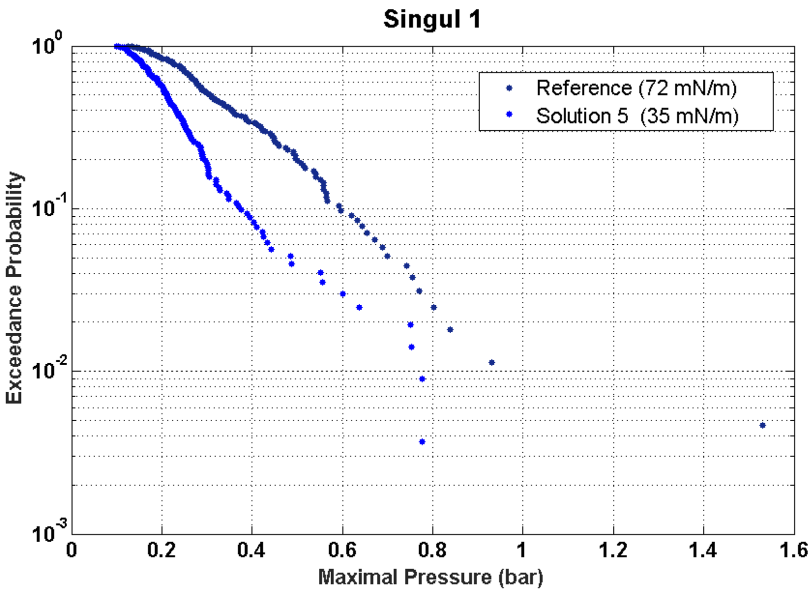
Coincident impact 1



Coincident impact 2

Effects of surface tension on Coincident Impacts at scale 1:40





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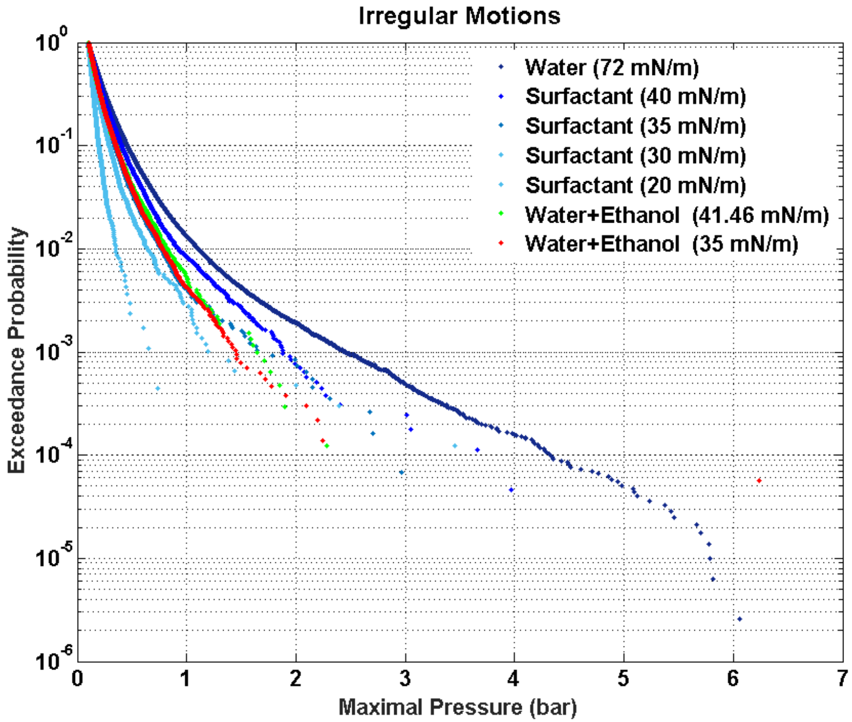
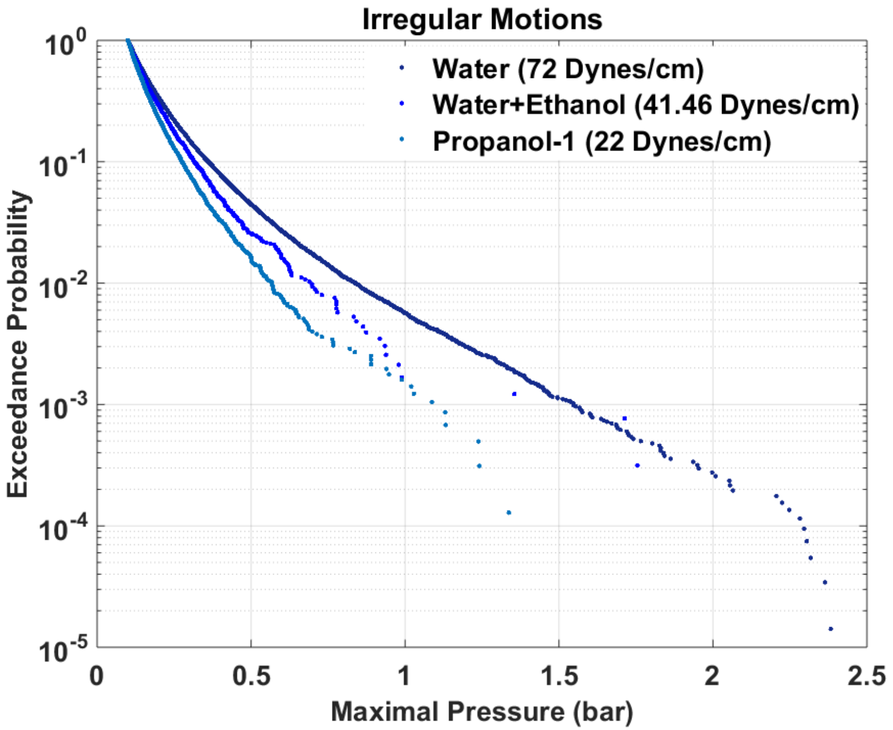
Effects of surface tension on pressure statistics for a complete irregular test



Scale 1:20



Scale 1:40

Conclusions

- **The main sources of variability are:**
  - Free surface instabilities due to the shearing gas flow before wave impacts
  - Fall of droplets after splashing
  - Production of bubbles
- **They are all related to surface tension**
- **The lower the surface tension, the lower the statistical pressure whatever the level of probability or the return period**
  - True for Single impact waves
  - True for any coincident impacts from irregular tests
  - True for complete irregular tests
- **Sloshing Model tests @scale 1:40 should be ideally performed with a surface tension at the interface about 800 times smaller than that at scale 1 to comply with Weber similarity**
- **Performing tests with water and a mixture of $SF_6 + N_2$ to get the right DR turns out to be a source of conservatism, considering this parameter separately**

Thank you for your attention

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