Numerical modelling - hazard and uncertainty

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Workshop – «Landslide-generated Impulse Waves in Reservoirs»
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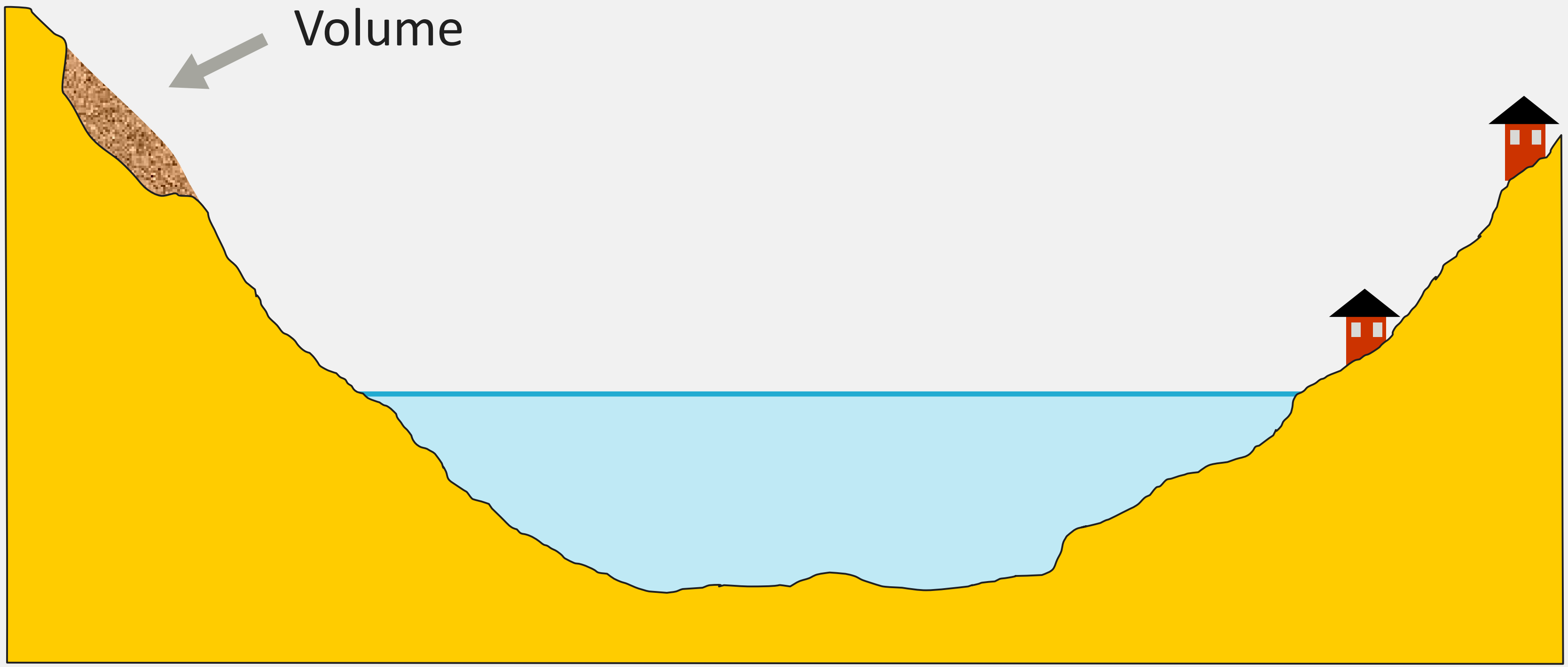
Modelling of landslide tsunamis



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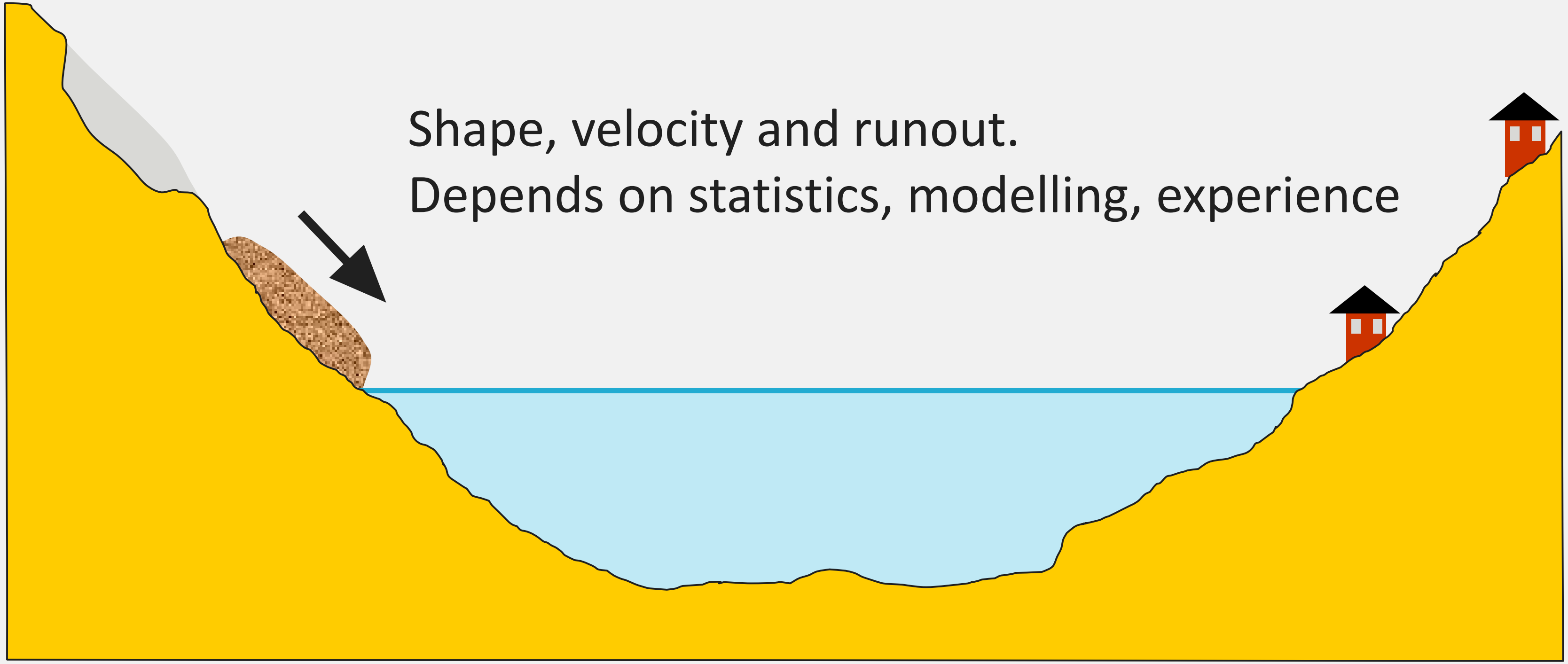
Landslide dynamics

Shape, velocity and runout.

Depends on statistics, modelling, experience



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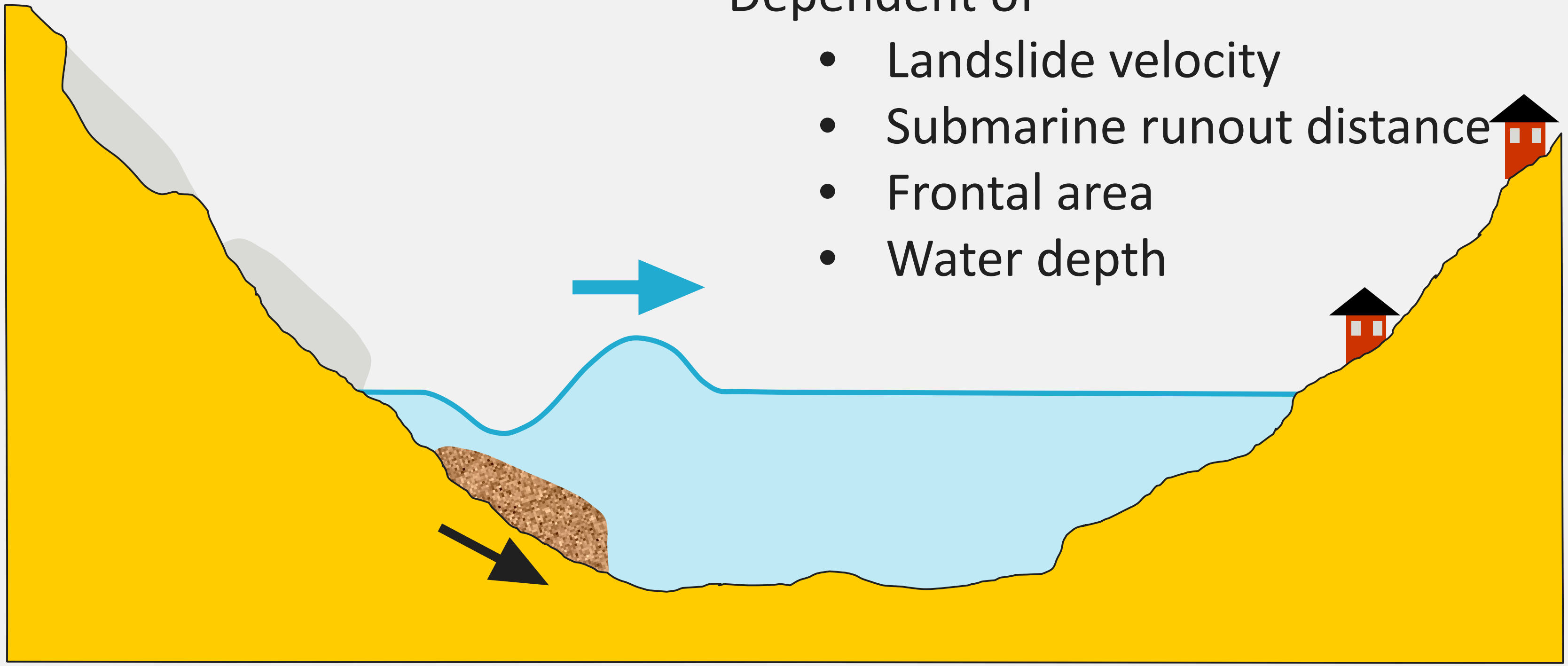
Tsunami generation

Dependent of

- Landslide velocity
- Submarine runout distance
- Frontal area
- Water depth



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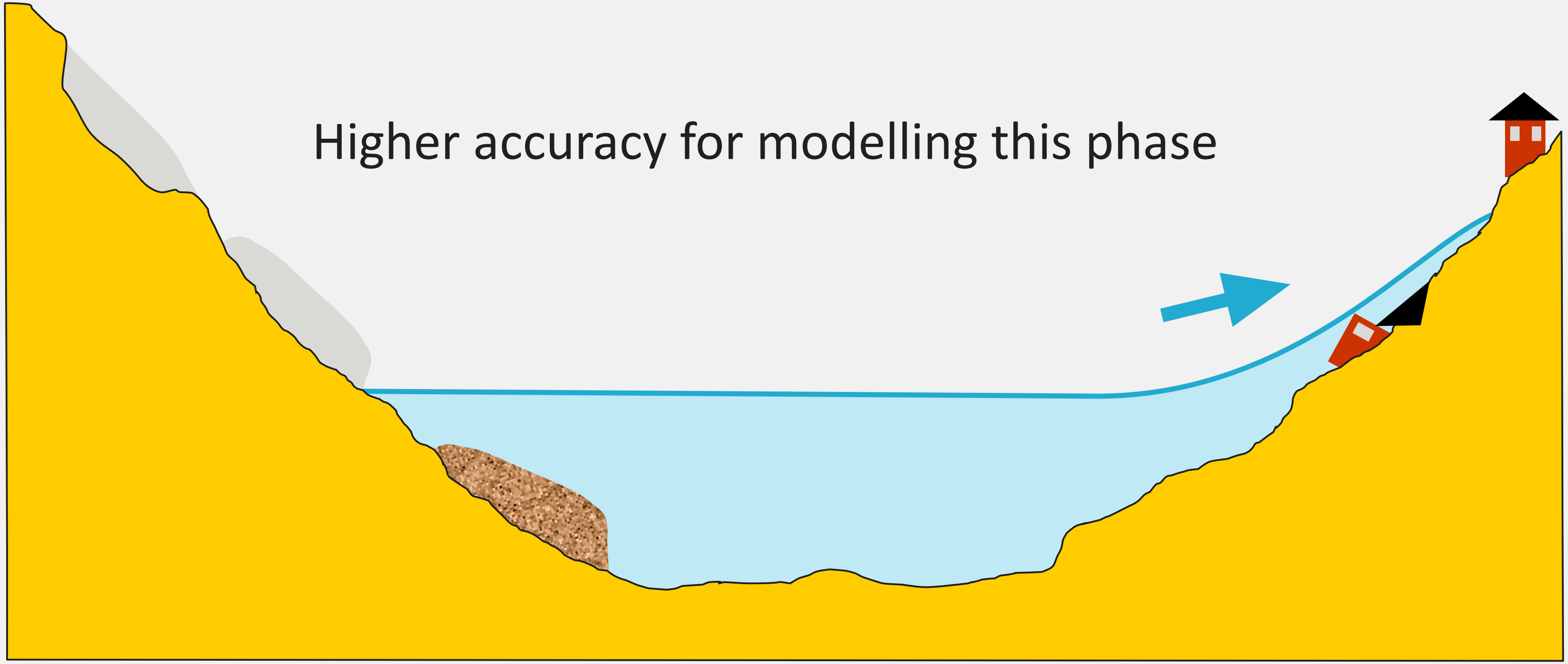
Tsunami propagation and inundation



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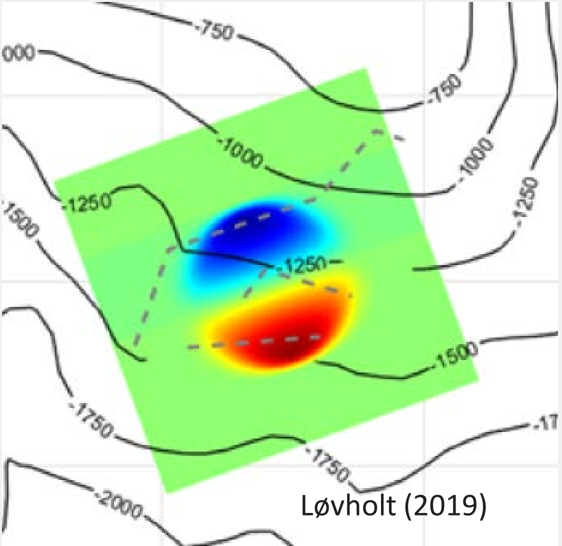
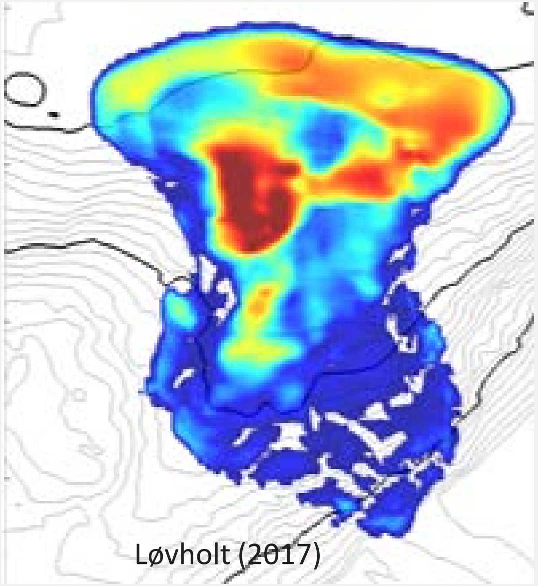
Rotational slumps:
Short time scales

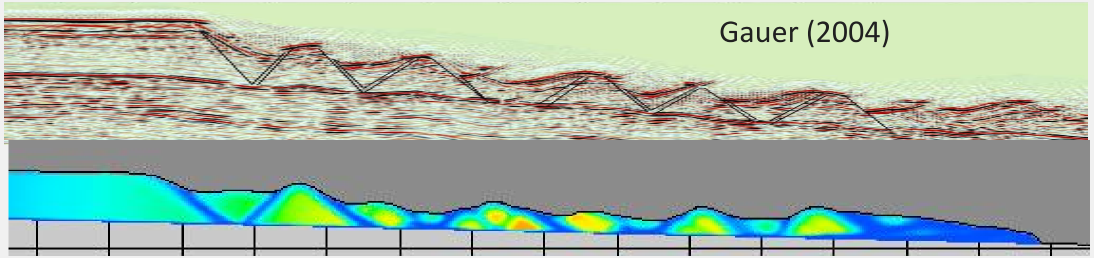


Landslide tsunami generation mechanisms
Great variety →
Dynamics of landslides of major importance for tsunami-genesis

Submarine debris flows:
Large volumes

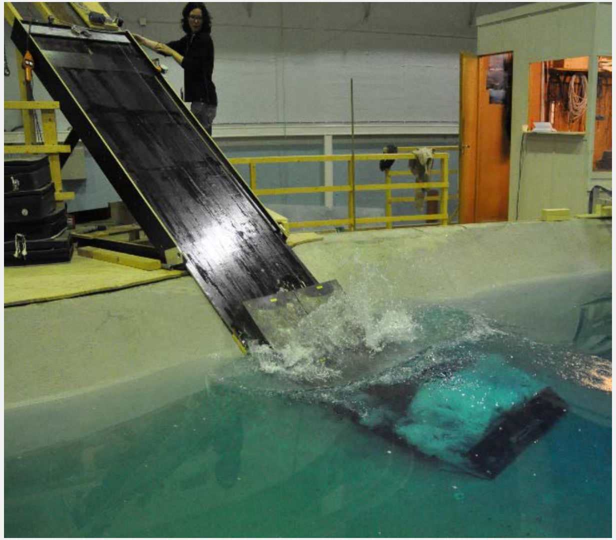


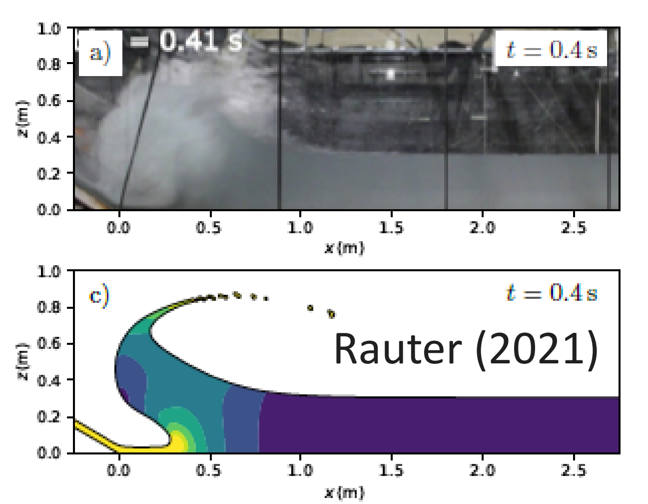
Staged, retrogressive motion:
Slow onset, less efficient



Subaerial landslide tsunamis

- Characterised by violent impact, cratering, and splashing
- More local than earthquake tsunamis
- Strong influence of:
  - Frontal slide area (and volume)
  - Landslide velocity during impact
- ***Landslide dynamics important for the tsunami generation***





Rauter (2021)

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Subaerial landslide tsunamis – key examples

18th century Japan volcano flank collapses

Oshima-Oshima 1741

Volume 2.5 km^3

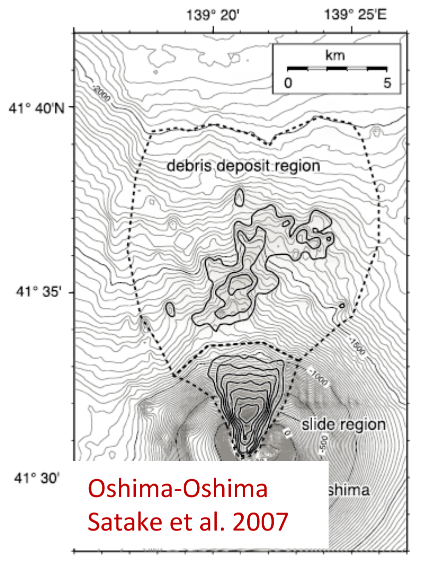
~2000 fatalities

Shimabara Bay 1792

Volume ~0.5 km^3

>4000 fatalities

Most fatal landslide tsunami in history



Oshima-Oshima
Satake et al. 2007

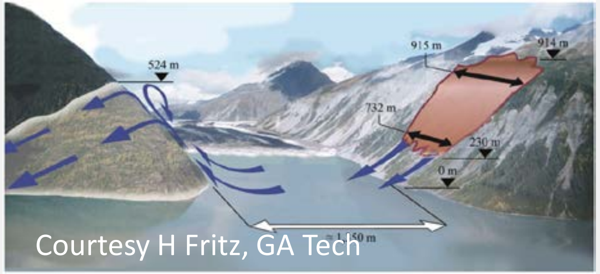
Western Norway: Loen 1905, 1936 and Tafjord 1934

174 Fatalities

Lituya Bay 1958

> 500 m run-up

Highest tsunami run-up height globally



Courtesy H Fritz, GA Tech

Many recent high run-up landslide tsunami events:

Paatuut, Greenland, 2000

Stromboli, 2002

Aysen fjord, Chile, 2007

Chechalis Lake, Canada, 2007

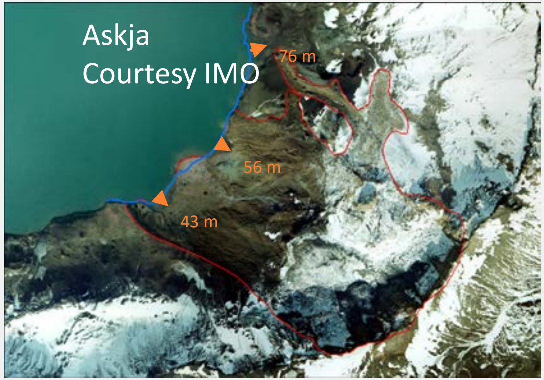
Askja, Iceland, 2014

Taan fjord, Alaska, 2015

Yangtze River, 2015

Karrat fjord, Greenland, 2017

Anak Krakatau, 2018



Askja
Courtesy IMO

Taan fjord
Courtesy C Larsen

Norway Tafjord 7. april 1934

Church boat MB Tafjord

INGVALD MØLLERSTAD/AFTENPOSTEN/SCANPIX; NTB/Scanpix;
http://www.dagbladet.no/magasinet/2008/03/27/530700.html

GIS method for hazard evaluation

Norway:

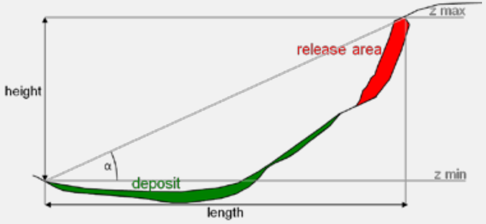
- 200.000 lakes/reservoirs + 25 000 km coastline
  - 20.000 lakes > 0.1 km^2

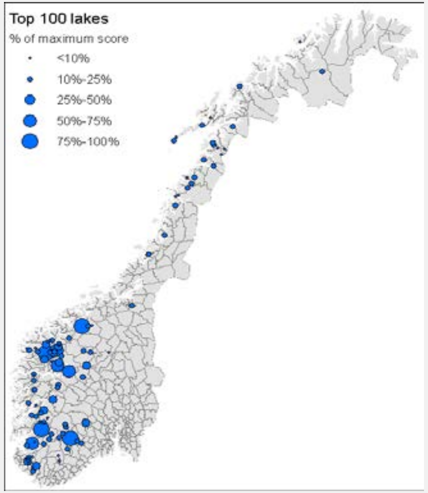
- Available data
  - Topography and maps of all lakes
  - Landslide data (limited)

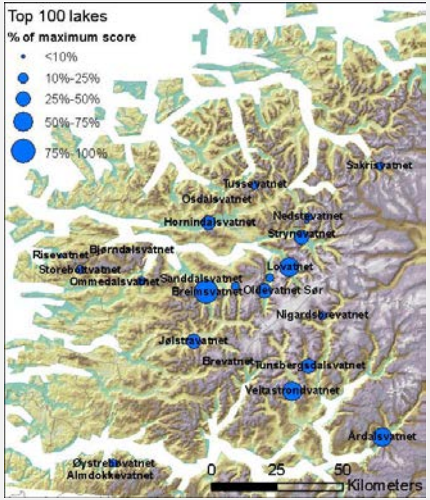
Mountain side north of lake Zakarias, Norddal.
Potential rockslides identified by NGI (2004)

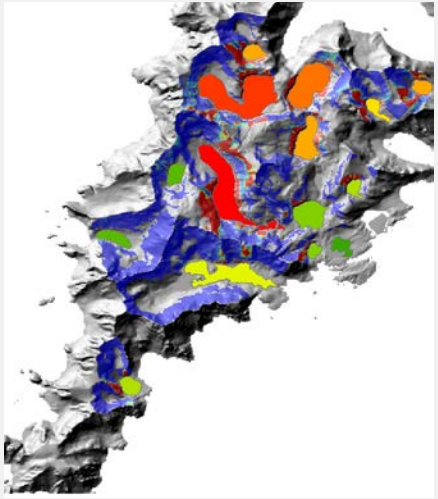
GIS rockslide tsunami hazard analysis

- GIS method for mapping potential rock slide / hazard in fjords, lakes and reservoirs
- Topography steep enough? Rockslide sources large enough?
- Run-out ratio H/L vs. volume
- Probability of certain volumes
- ➔ Topographic rock slide potential for each lake
- *What lakes should be analysed further*
- Co-sponsored by NVE









Romstad, Harbitz & Domaas (2009) NHESS 9

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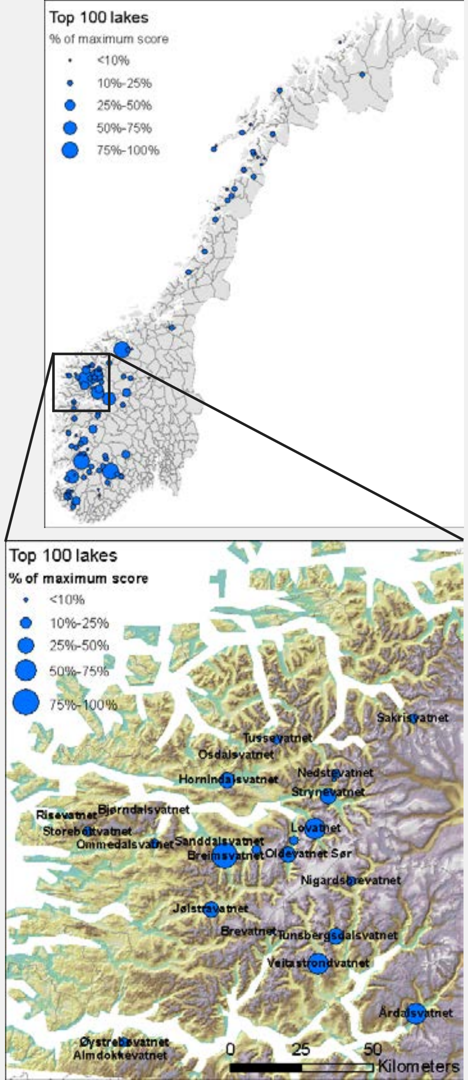
Results

- ~12 000 lakes (6%) have a tsunamigenic landslide potential
- Most lakes provide a low score (< 0.1% of the maximum)
  - 100 lakes with score >10% of maximum
  - 46 of these are hydro electric power dams;
    - – 20 associated with possible large consequences
- – Lakes with known hazard (e.g. Lovatnet) are among the lakes with very high score



Romstad, Harbitz & Domaas (2009) NHESS 9

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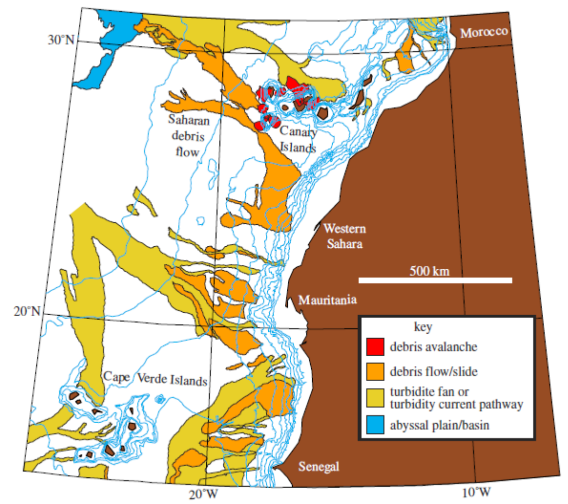
Landslide dynamics models

- Block models
- Cohesive fluid dynamics models (clay dominated)
  - E.g. Bingham fluids, Hershel-Bulkley models
- Frictional collisional fluid dynamics models (particle interaction dominated)
  - Wide range of models, rheologies, and complexity (e.g. Savage-Hutter, μ(I), pore fluid effects, entrainment, 2D, 3D…)
- Important for submarine landslides
  - Hydrodynamic resistance

Saharan sand dominated slides, Masson et al. (2006)



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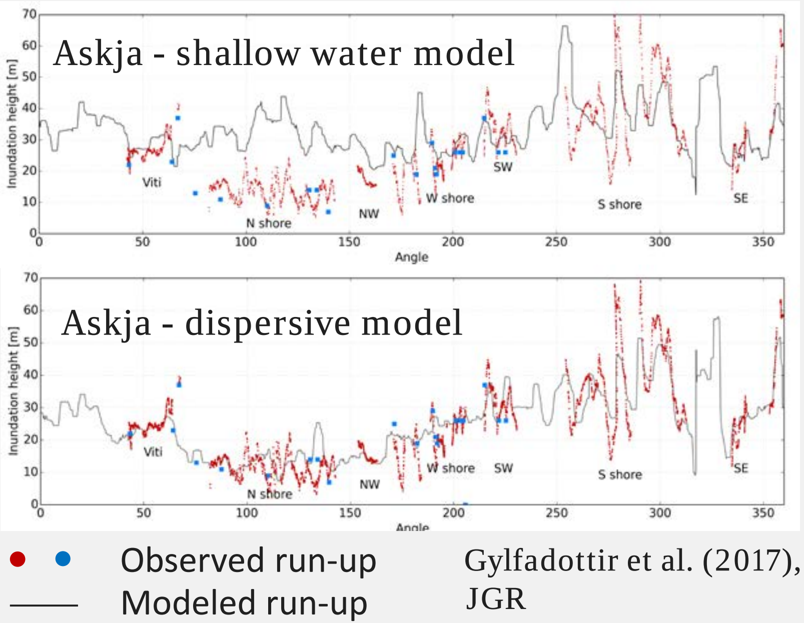
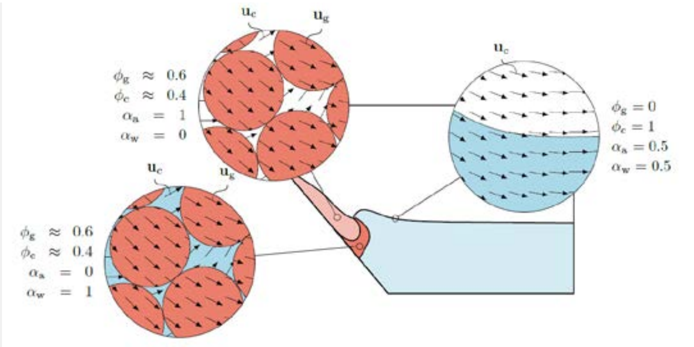
Tsunami models

- Shallow water type models – 2HD
  - Efficient and most used, but lack essential aspects important for landslide tsunamis
- Boussinesq type models – 2HD
  - Include **frequency dispersion**
- Computational Fluid Dynamics (CFD) models – 3D
  - Three dimensional with few simplifying assumptions
  - Landslide dynamics, complex rheology, and tsunami generation can be fully integrated



Gylfadottir et al. (2017), JGR

Rauter et al. (2021): 3D CFD model



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CFD model in OpenFOAM

Rauter et al. (2022)

- As PhD student at NGI, Matthias Rauter developed a novel landslide tsunami model (funded by H2020 EU project SLATE)
- Models both the landslide and wave (generation, propagation and runup including water/particle interaction)
- Basis for filling gap in basic physical understanding

Lake Askja landslide 2014

Tsunami simulation of 2014 Lake Askja tsunami

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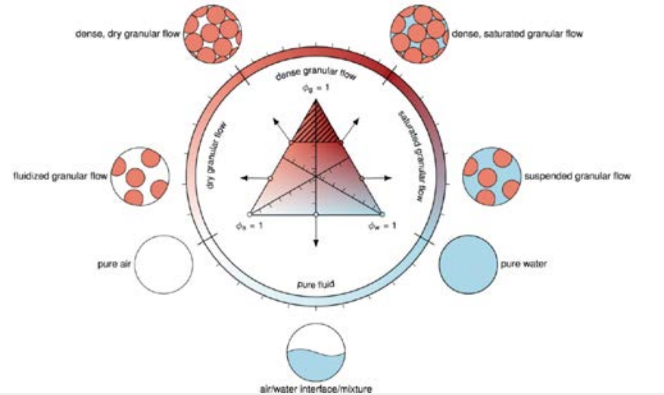
Main aspects of the model

Rauter et al. (2022)

Multi-phase coupling,
porous landslide



Advanced landslide rheology from
solid to granular behaviour

$$\nu_g = \mu(I)\,\frac{p_s}{2\,\bar{\phi}\,\rho_g}\,\frac{1}{\|\mathbf{S}_g\|},$$

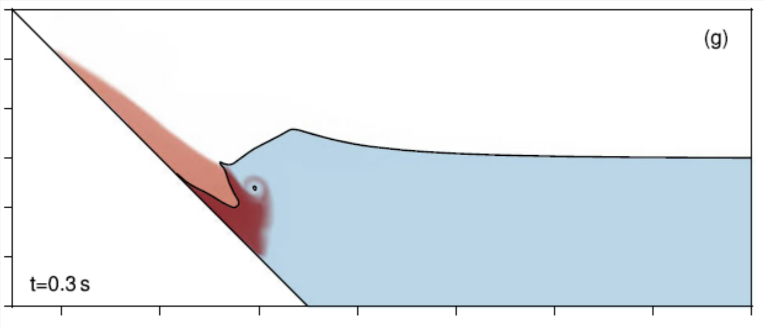
$$\mu(I) = \mu_s + \frac{\mu_d - \mu_s}{I_0/I + 1},$$

$$I = \frac{2\,d\,\|\mathbf{S}_g\|}{\sqrt{p_s/\rho_g}}.$$

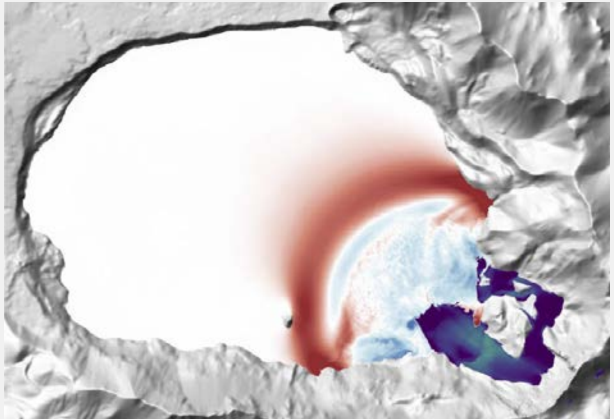
$$\mathbf{S}_g = \frac{1}{2}\left(\nabla \mathbf{u}_g + (\nabla \mathbf{u}_g)^T\right) - \frac{1}{3}\nabla\cdot\mathbf{u}_g\,\mathbf{I},$$

…

Simulating lab scale experiments



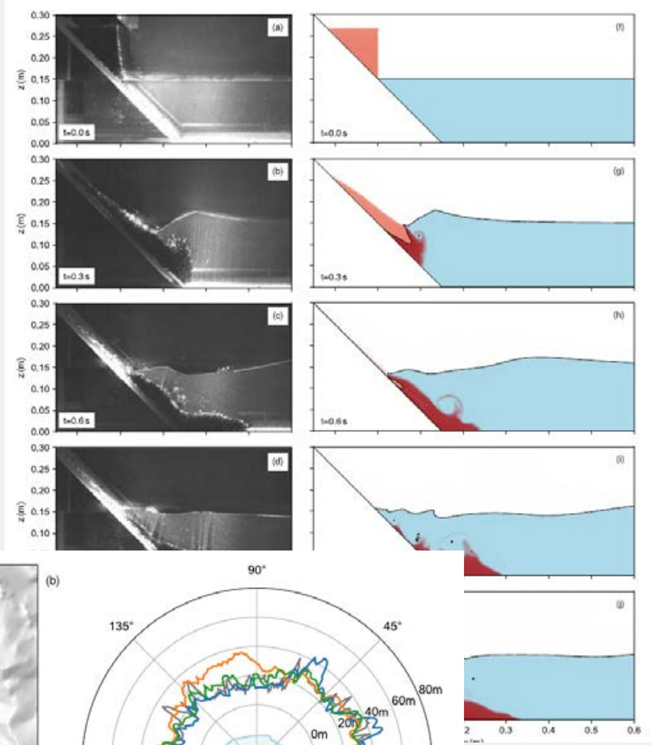
To full 3D simulations

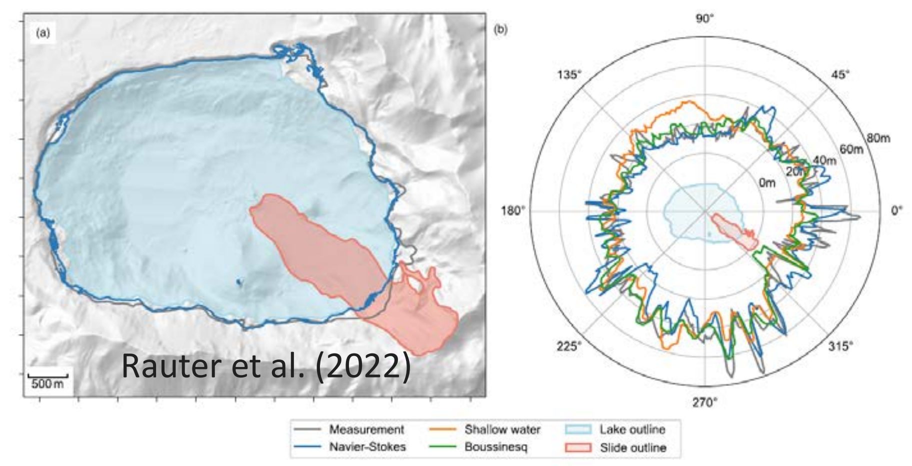


Main scientific findings

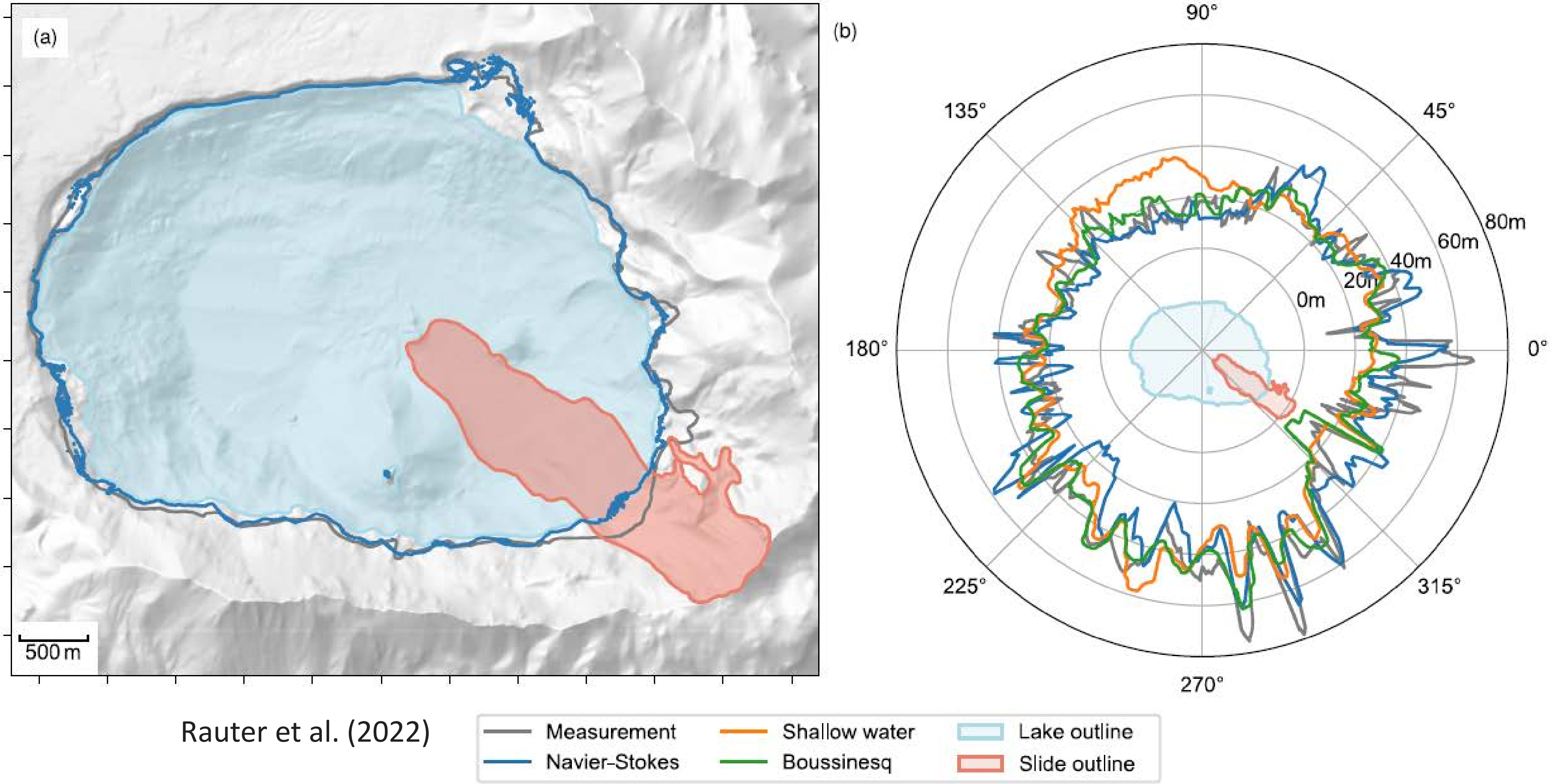
- Matching consistently **both landslide AND tsunami observations** from the laboratory to the field scale
- Close agreement with both landslide run-out and wave observations
- Advanced landslide material behaviour, direct simulation with **no attempt to calibrate** the landslide parameters

Viroulet et al. (2013) Ratuer et al. (2022)





Rauter et al. (2022)



Rauter et al. (2022)

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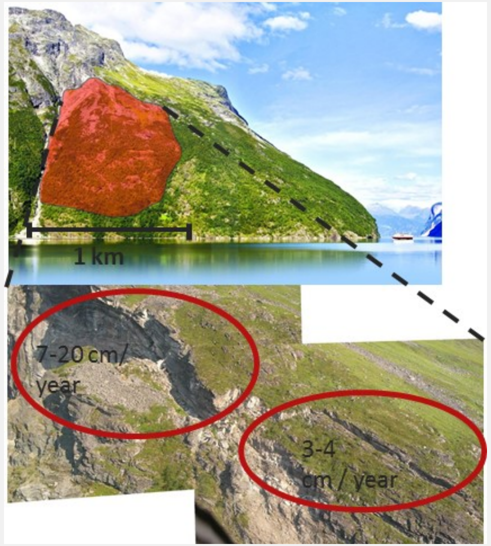
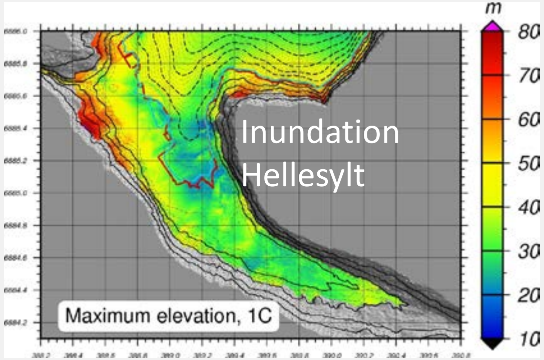
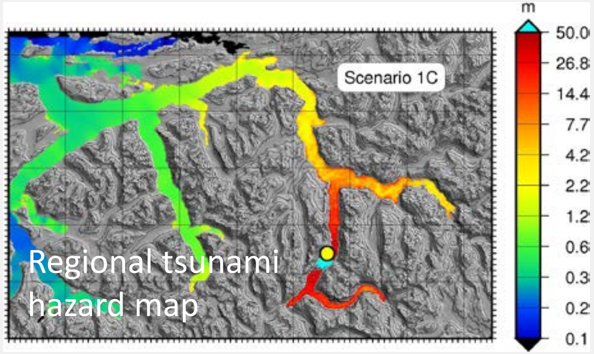
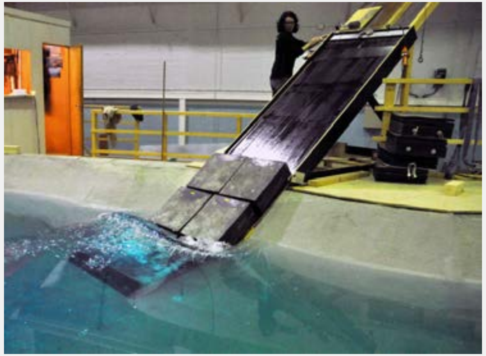
The Åknes rockslide

- Unstable rock slope 150 - 900 m.a.s.l
- Large movements /deformations
- Largest volume > 50 Mm^3
- Advanced computational tools needed
- Laboratory experiments 2D and 3D
    - Calibration and verification of numerical models
- A large number of scenarios and locations analysed









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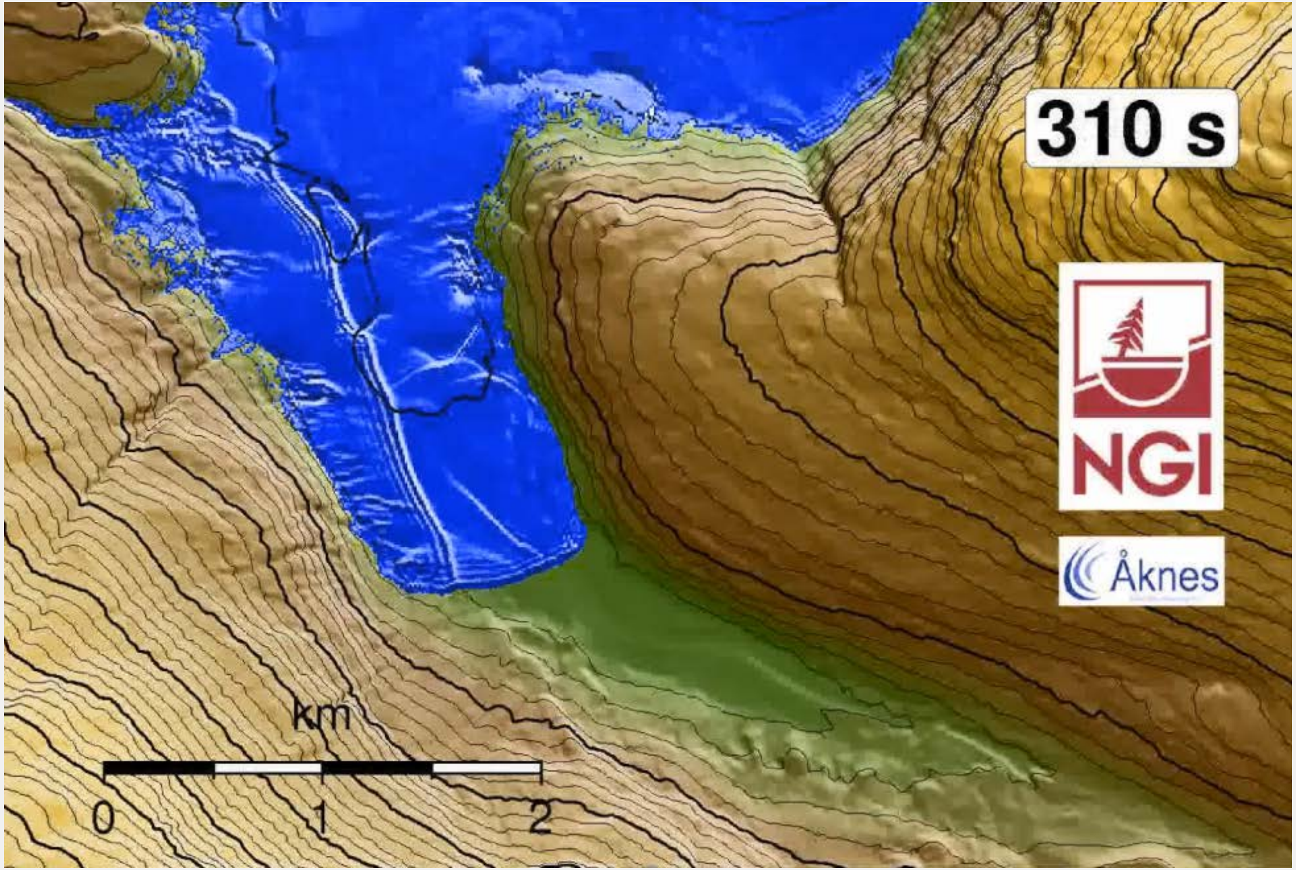
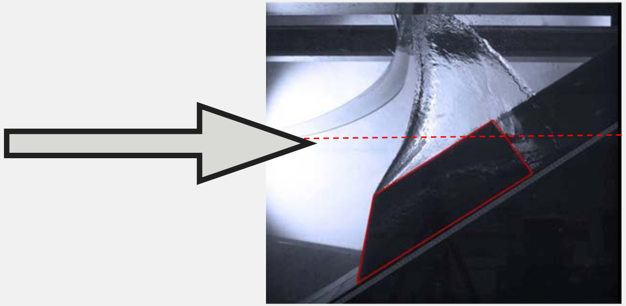
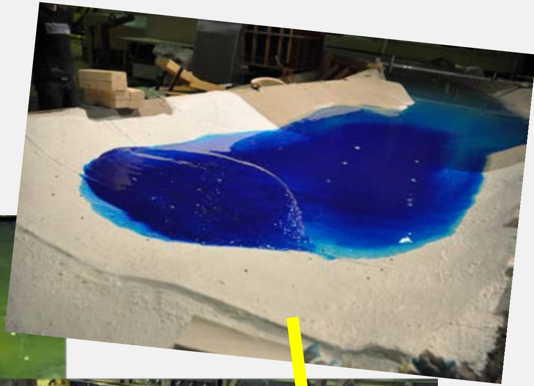
Åknes tsunami – run-up in Hellesylt

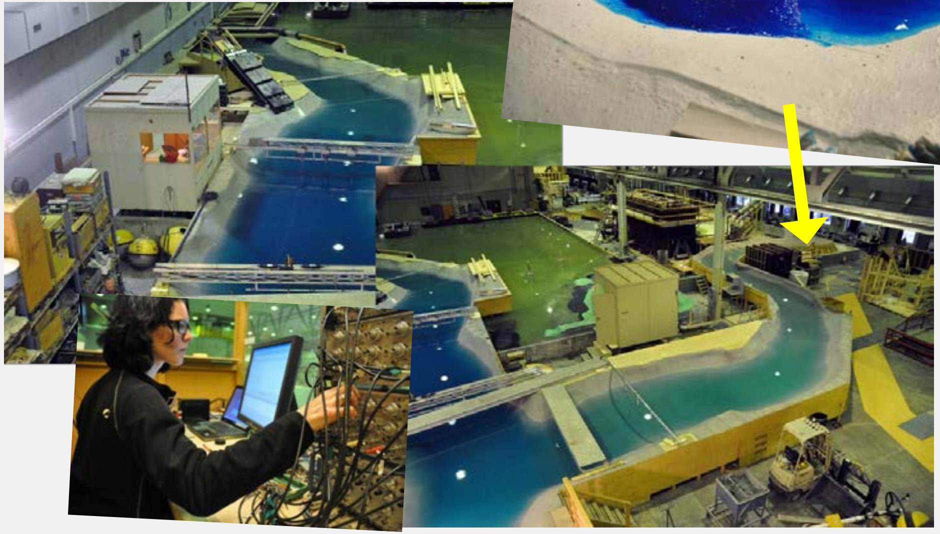


Åknes – laboratory experiments

- 2D: Hydrodynamic laboratory, University of Oslo
- 3D: SINTEF – Coast and harbor laboratory
  - Scale 1:500
  - “block-slide”
- Validation of and input for numerical models







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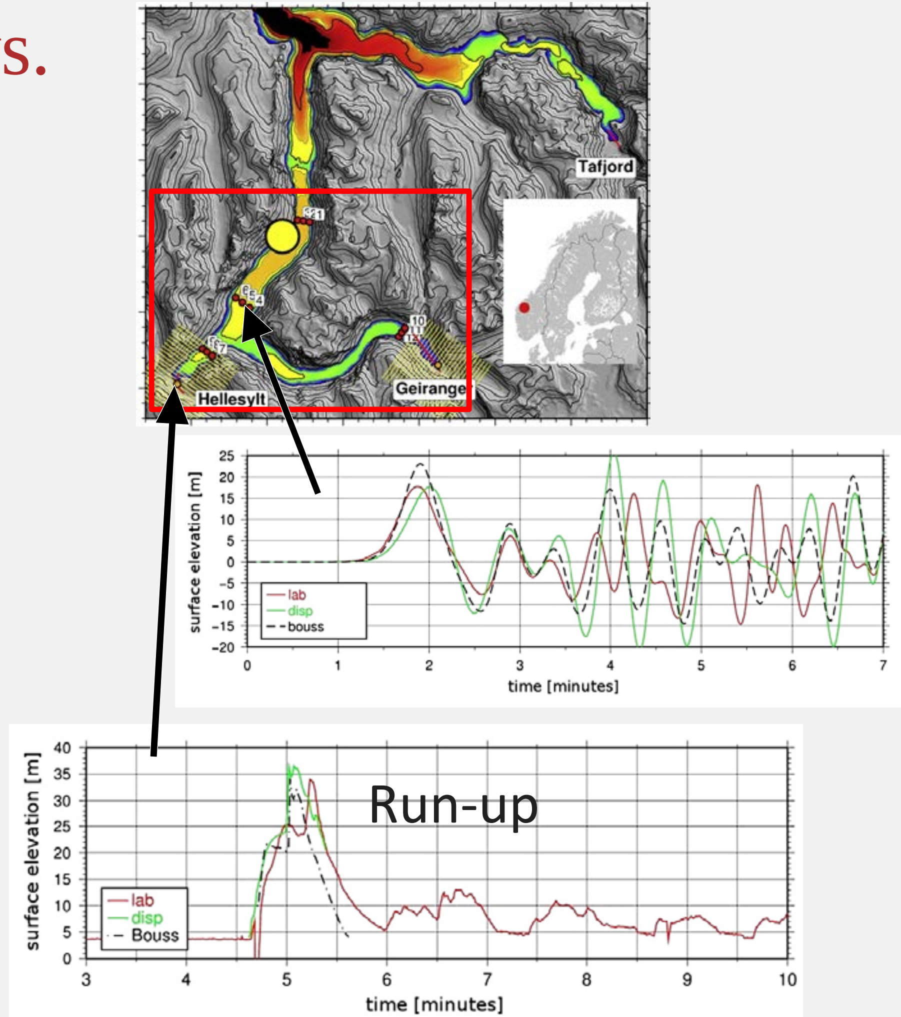
Laboratory experiments vs. numerical models

- Laboratory model inside red box
- Measured surface time histories both in fjord and in inundation area
- Demonstrate governing parameters for propagation and model benchmarking
- No tuning of numerical model – reproduce laboratory experiments as close as possible



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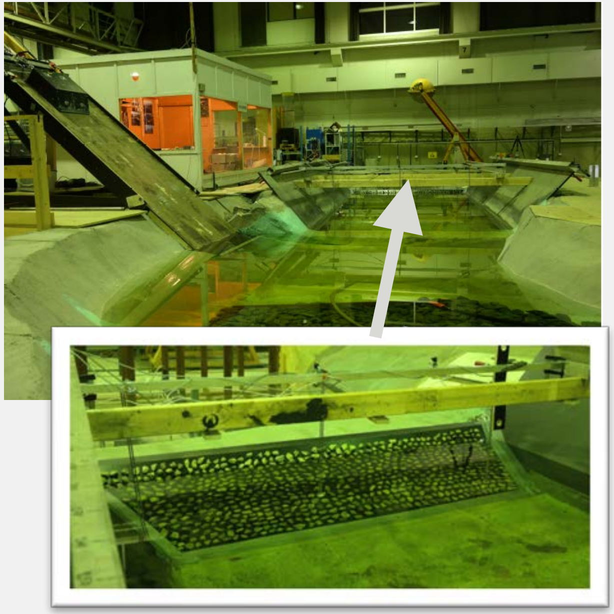
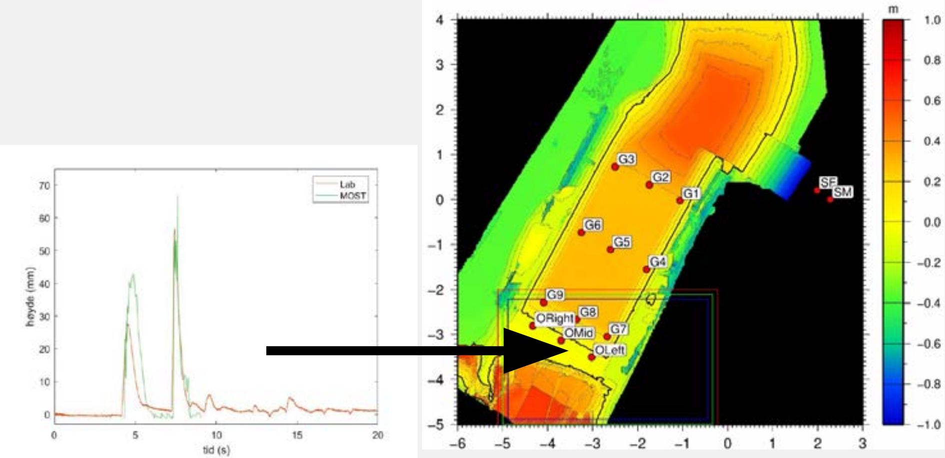
Dam overtopping
– laboratory experiments vs. numerical modelling

- Master thesis
  - Ragnhild Hammeren (2016), NTNU, Trondheim
- Rebuild of Åknes model
- Numerical modelling by NGI





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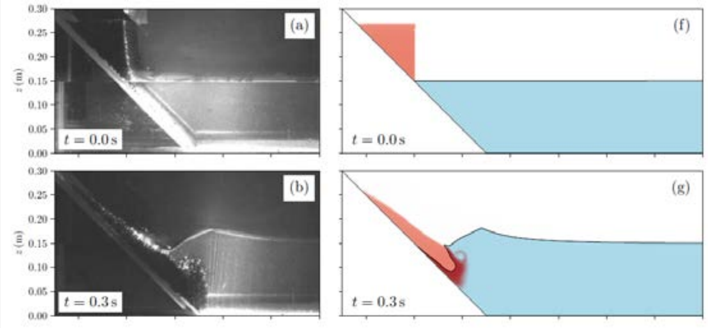
Testing landslide tsunami models

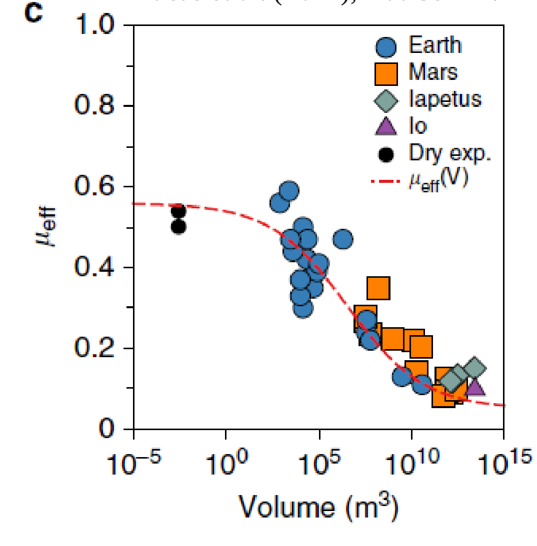
http://www1.udel.edu/kirby/landslide/problems.html

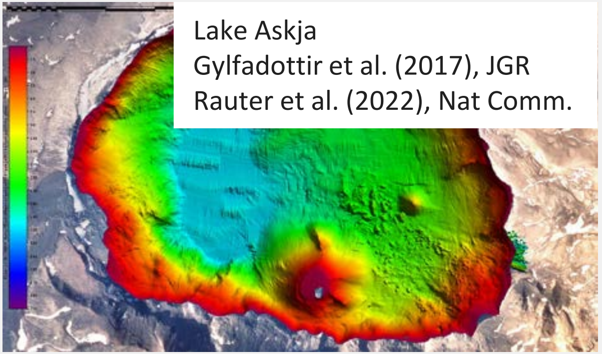
- Benchmark cases (NTHMP - US)
  - Mainly idealized laboratory
  - Tailored towards tsunami-genesis, less on landslide dynamics and material behavior
- Friction of landslides depends on its size, need modelling well documented full scale events
  - **Lake Askja 2014**: confined in lake, accurate volume and run-up measurements, “full scale lab”
  - Other examples, Taan fjord, Anak Krakatoa, …

Rauter (2021), PhD Thesis

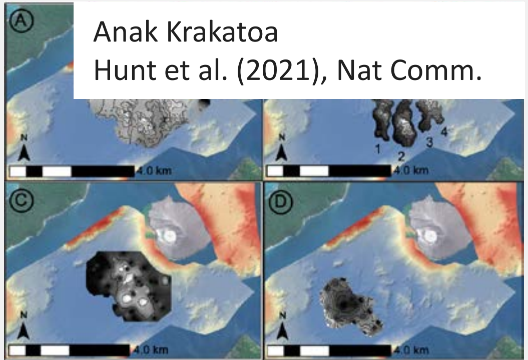


Lucas et al. (2014), Nat Comm.



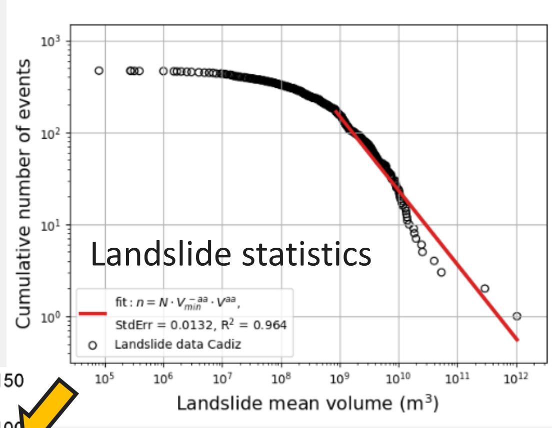


Lake Askja
Gylfadottir et al. (2017), JGR
Rauter et al. (2022), Nat Comm.



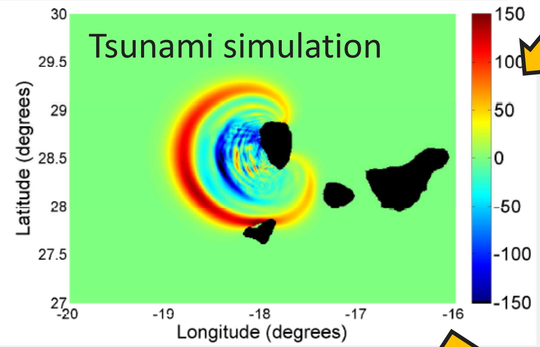
Anak Krakatoa
Hunt et al. (2021), Nat Comm.

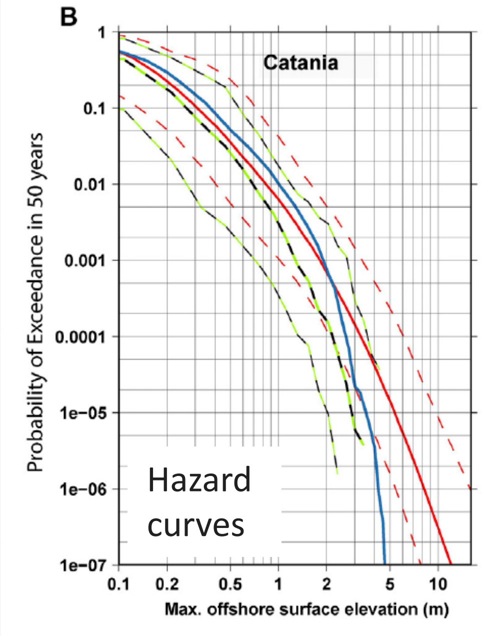
Landslide Probabilistic Tsunami Hazard Assessment (LPTHA)



LPTHA in brief:

1. Generate a synthetic set of sources (different volumes and generation mechanisms)
2. Define annual source probabilities – use statistics of past data
3. Simulate the wave propagation for each source
4. Aggregate probabilities from all simulations to hazard curves



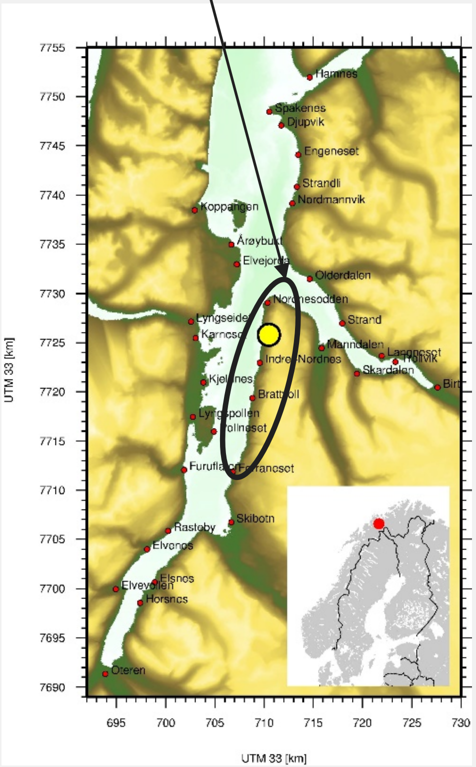


Landslide Probabilistic Tsunami Hazard Analysis (LPTHA) example

Løvholt et al., 2020, Landslides

- Goal – estimate tsunami probability of occurrence
- Include the uncertainties in forecasting
- Area of interest - Lyngen Norway
- Four different unstable rock slopes
  - Volumes 0.8-6 Mm^3
  - Frequencies estimated prior to our analysis by means expert judgement
  - Average frequencies 1/633 yr^{-1} -1/2315 yr^{-1}

Unstable rock slopes



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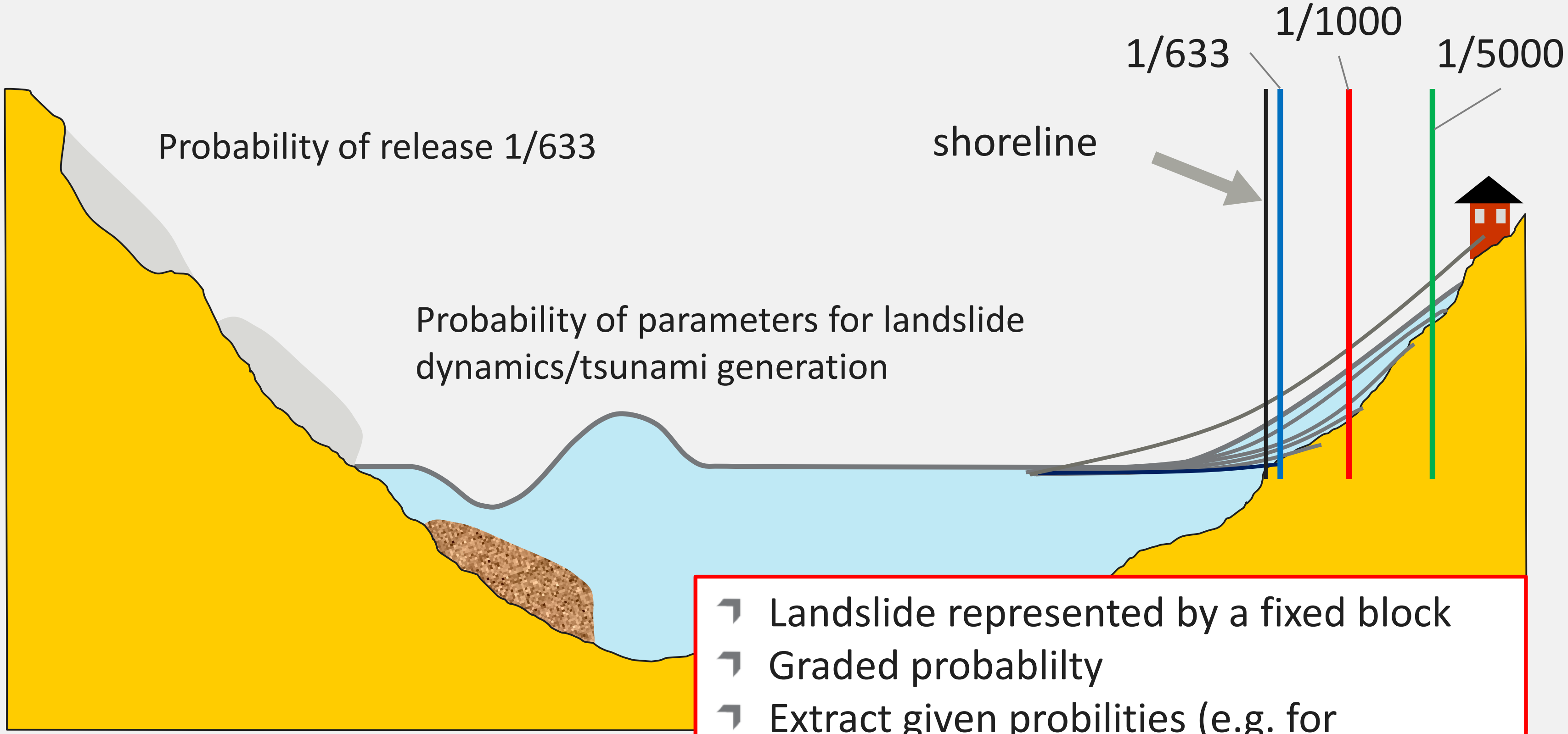
Schematic LPTHA



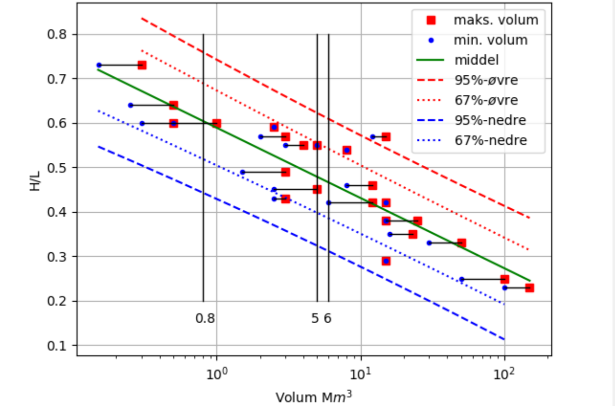
- Landslide represented by a fixed block
- Graded probablilty
- Extract given probilities (e.g. for restriction on Plan and Building Act)

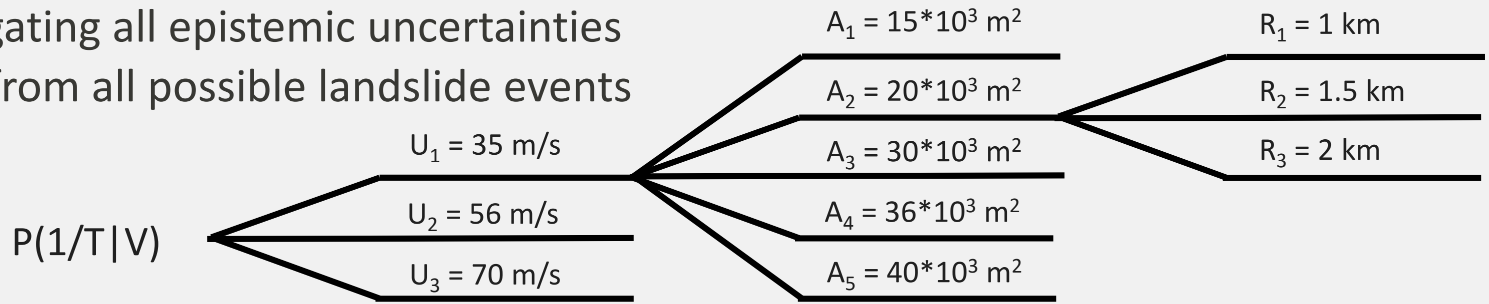
Establishing and aggregating uncertainties

Løvholt et al., 2020, Landslides

- Epistemic (systematic) uncertainty – landslide dynamics
  - Block slide – much more controlled behaviour of the slide (shape, run-out, velocity)
  - Run-out distance R – fitted towards past run-out
  - For the impact velocity U and frontal areas A: Sensitivity studies based on modelling and experience from modelling past events
- Event tree analysis
  - Aggregating all epistemic uncertainties
  - Rates from all possible landslide events

Uncertainty in landslide run-out distance (H/L) from past data





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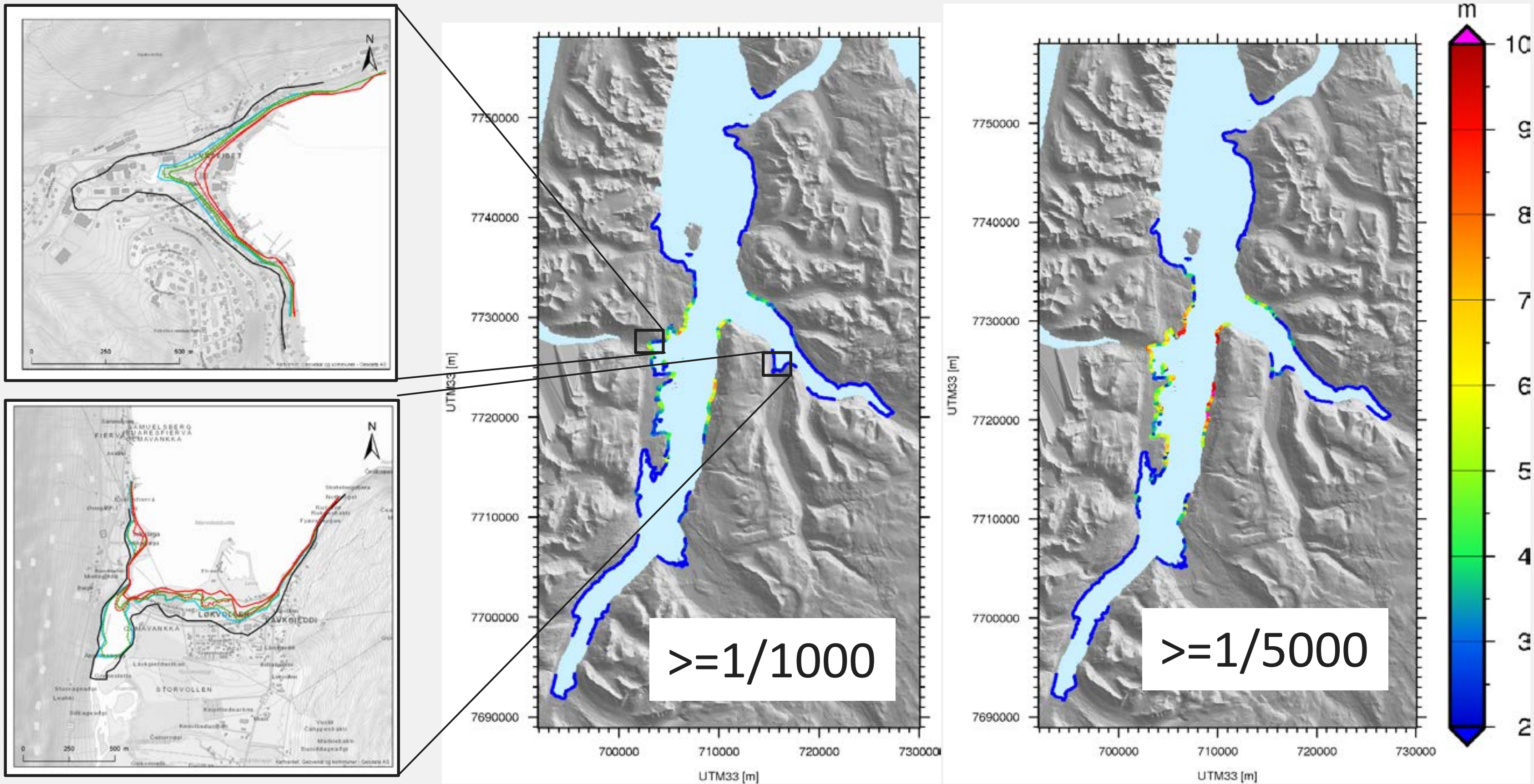
LPTHA results for Lyngen – local inundation analysis aggregated: 31 locations x 600 events

Løvholt et al., 2020, Landslides



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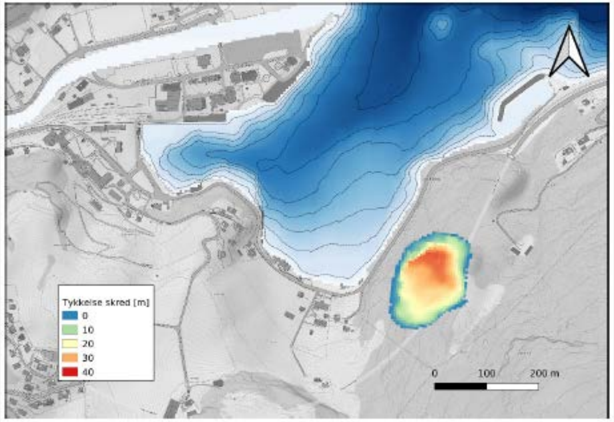
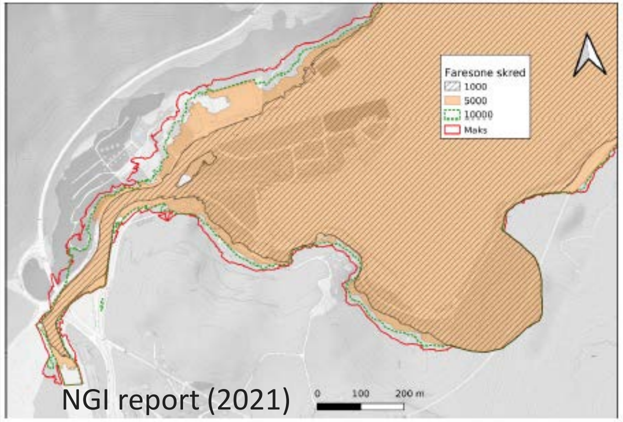
Example Stiksmoen, Flåm – western Norway

- 400.000 m^3
- Estimated annual probability of release, p=1/240
- Maximum line – highest runup of all 600 scenarios (p -> 0)
  - Worst case scenario?
  - Used for evaluation of evacuation zones and locations for critical infrastructure (e.g. hospital, p=0)





NGI report (2021)

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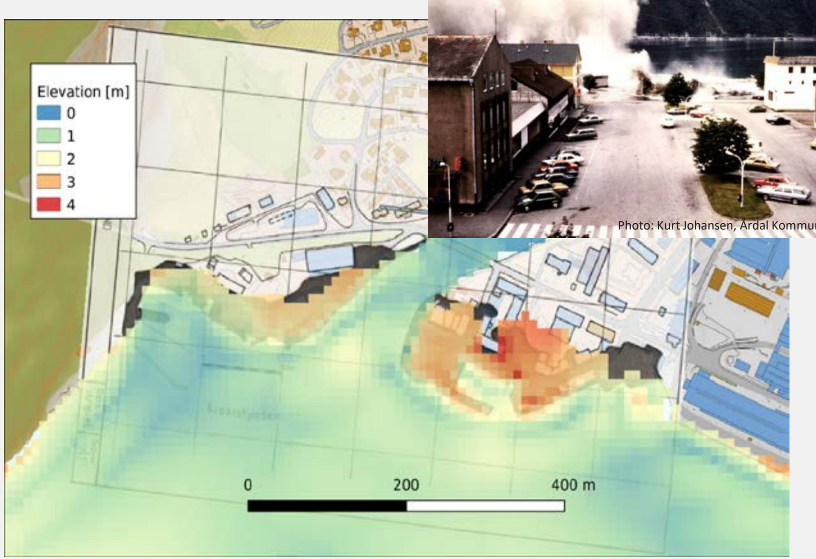
Calibration of LPTHA

- LPTHA for Norwegian landslide tsunamis
- Ongoing work
- Using known and documented events
- Systematic analysis
  - Common correction factors to frontal area?
  - Calibrate the LPTHA so that the event i close to the median values of the runup?
- Using both the OpenFOAM model in addition to depth averaged models for landslide and tsunami



- ✓ Skafjell, 1731
- ✓ Tjelle, 1756
- ✓ Taford, 1934
- ✓ Rissa 1978
- ✓ **Årdalstangen, 1983**
- ✓ Katlenova, 1998
- ✓ Statland, 2014
- ✓ Geiranger, 2017

Tsunamis in reservoirs

- Main modelling issues in a fjord are also present in a lake/reservoir
- Tsunami origin both from subaerial and submarine landslides
- Models for tsunami run-up can handle ***dam overtopping***
  - Caclulate forces on dam itself and infrastructures on dam crown during overtopping
  - Can also be coupled to modelling of the downstream flooding
- LPTHA is a good methodology for treating uncertainties systematically also for reservoirs
  - Most likely or worst case scenario, or a given return period?

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Conclusions

- Landslide dynamics accounts for large variability
  - Wide range of sources and mechanisms - more complex and diverse than earthquakes
- Systematic uncertainty is linked to material parameters and hydrodynamic resistance
- Hindcasting past landslide run-out implies large uncertainties
- Tsunami data can be used to narrow down this uncertainty range
- With better models, we are on the pathway to understand well the generation mechanisms, but difficulty remains
  - Scaling up from the lab
  - Incorporating real geomaterial behaviour and phase transitions
- LPTHA is the most rational tool to manage these uncertainties in forecasting

#påsikkergrunn

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