Politecnico di Torino

Dams & Reservoirs DAY 2025
Water and Energy security for Europe

OPEN DAY ON DAMS



Dams and environment: engineering solutions for the future

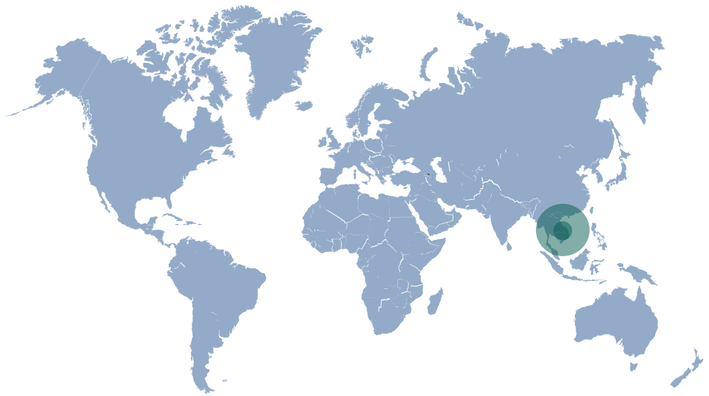
TORINO , 28 maggio 2025

Dam Break Wave Propagation: Scenarios and Predictions

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ITCOLD – II Concorso Fotografico

01 ADDRESS DAM RISK



RECENT DISASTERS:

Laos 2018- Champasak Province

- Occurred on 23 July 2018 on an earth-filled dam, minor segment of a larger hydroelectric dam system under construction.
- The collapse illustrates risks involved if construction is "unable to cope with extreme weather conditions… becoming more frequent“ (The international River organization).
- Flooded area characterized by sparse or clustered vegetation



01 ADDRESS DAM RISK



RECENT DISASTERS:

Brazil 2019- Brumadinho dam

- Occurred on January 25, 2019, in the Brazilian municipality of Brumadinho, Minas Gerais.
- The tailings dam at the Córrego do Feijão iron ore mine, owned by Vale S.A., failed releasing 12 million cubic meters of tailings.
- The collapse resulted in extensive environmental damage and waterways contamination.



01 ADDRESS DAM RISK



RECENT DISASTERS:

Ukraine 2023- Kakhovka Dam

- Breached on 6 June 2023 caused flooding along Dnieper river.
- According to various experts, the dam has been blown up by Russian forces to hinder Ukrainian counter-offensive although the attack was never acknowledged.
- The wave involved urban areas with sparse vegetation





RECENT DISASTERS:
Libya 2023 - Derna Dam

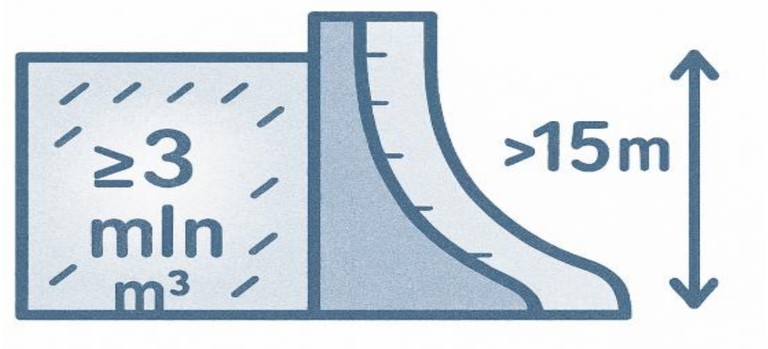
- Catastrophic failure of two dams in Derna, Libya on the night of 10–11 September 2023.
- In the aftermath of Storm Daniel
- The event occurred in a highly dense urban area



SEEKING FOR DATA

Where information on dam collapses can be found?
Many datasets are available:

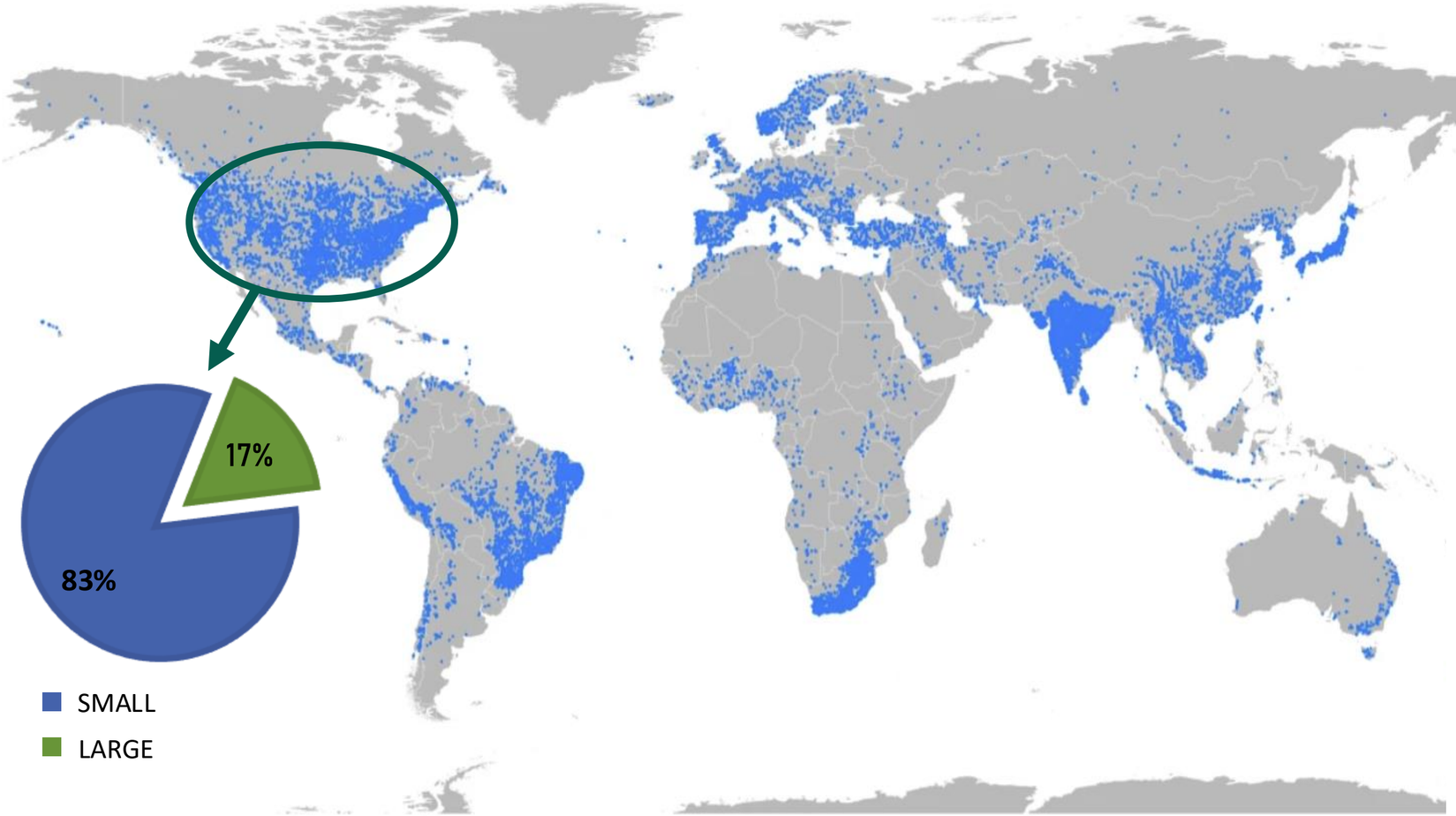
- ARIA collect damaging events including dam failures.
- NPDP collect USA and world dams over hydraulic related failures.
- NID more detailed dam catalogue for USA.
- ICOLD international database for large dams



We should distinguish between small and large dams

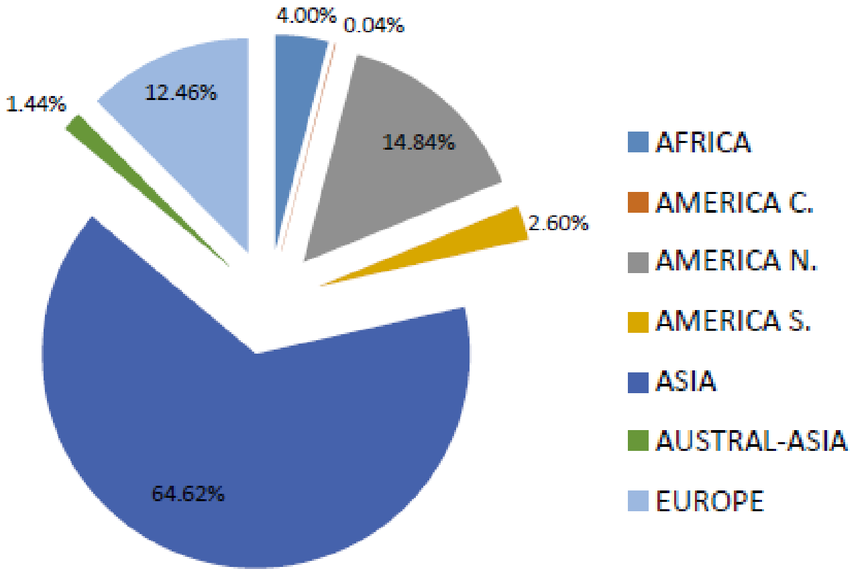
ICOLD define a large dam as “A dam with a height of 15 meters or greater from lowest foundation to crest or a dam between 5 meters and 15 meters impounding more than 3 million cubic meters”

GENERAL STATS – World distribution



World dam's databases report, only or mostly, large dams

For the USA where a more detailed catalogue is available small dams count for the 83%



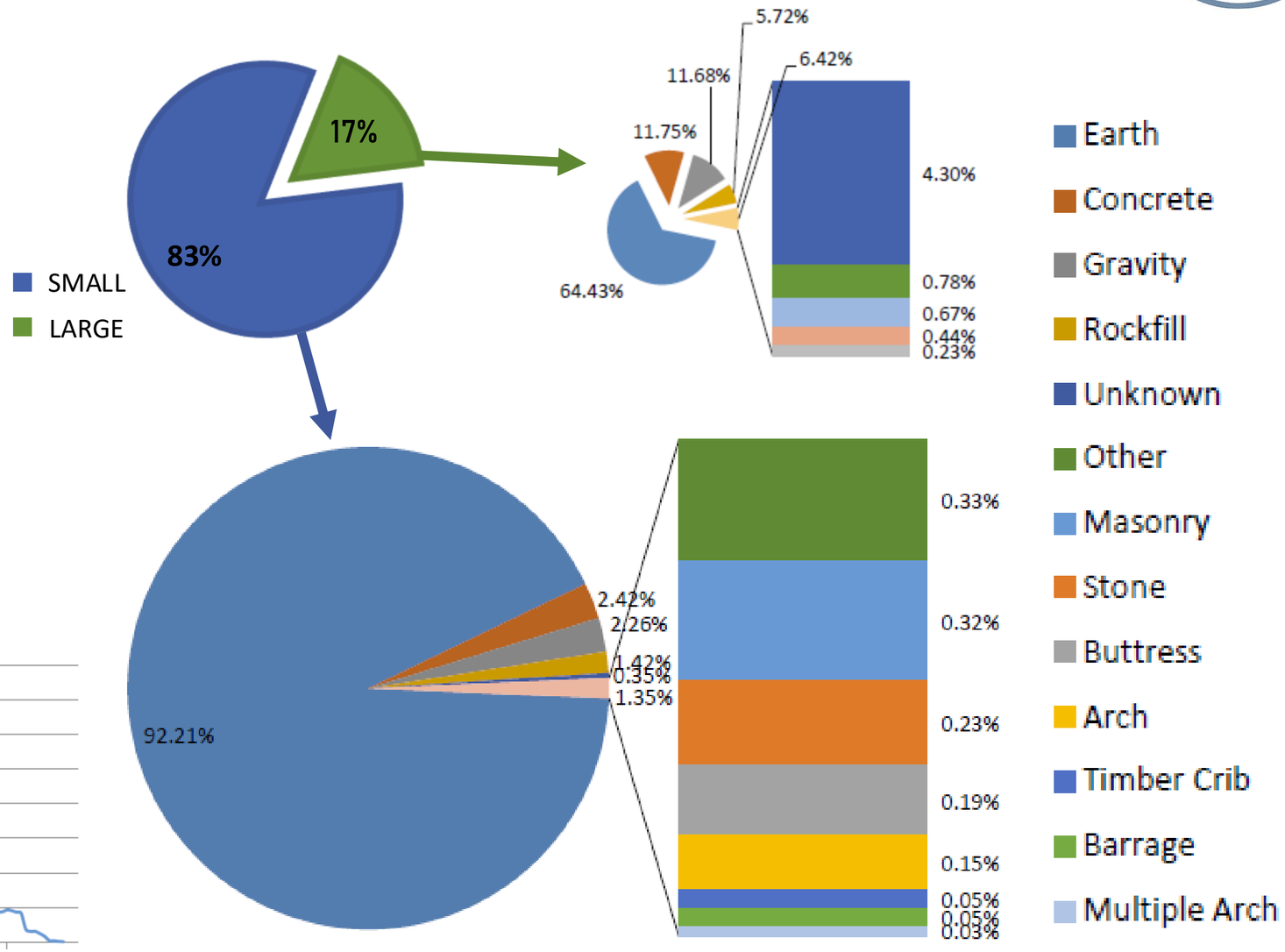
Zhang, A. T., & Gu, V. X. (2023). Global Dam Tracker: A database of more than 35,000 dams with location, catchment, and attribute information. *Scientific Data*, *10*(1), 111.

01 ADDRESS DAM RISK

GENERAL STATS

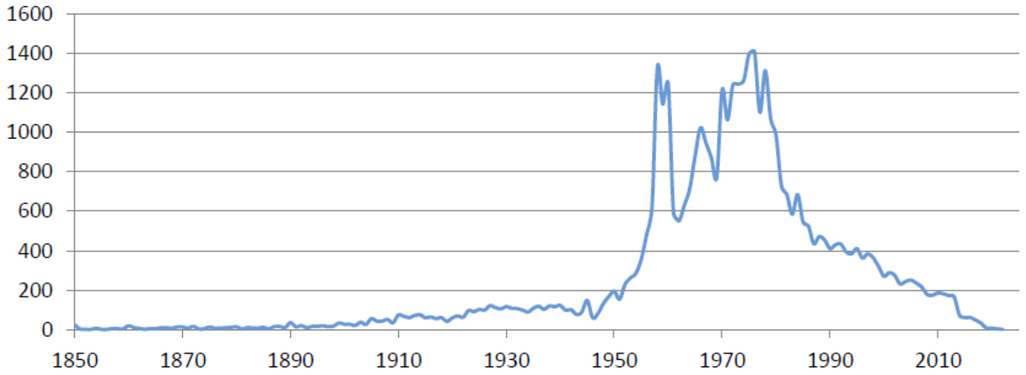
– Typology

The majority of dam are earth dams, from 65% among large dams up to 92% among small dams



– Age

Most of dams has been built during from 50's to 80's



Number of dams by year of costruction

01 ADDRESS DAM RISK

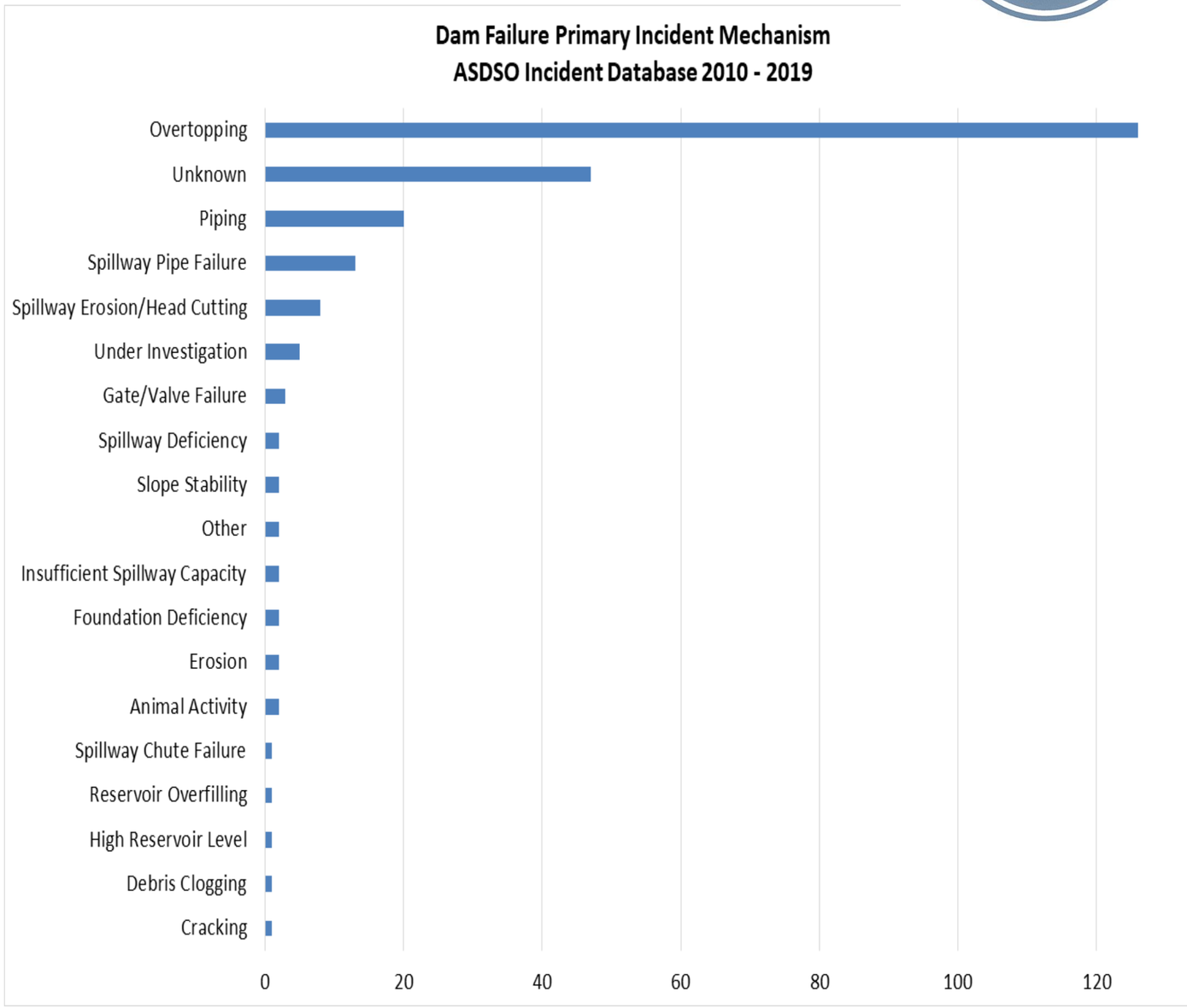
DAM FAILURE

The cumulative failure rate (CFR) of large dams stayed fairly constant, falling in the range of 1.2% to 1.8% as of end-of-2020

The cumulative failure rate of small dams globally remains hard to define given the lack of data

For the USA 94% of dam failure from 1848 to 2017 occurred on small dams with an almost double CFR (1.9% compared to 1.0%)

Most frequent dam failure mechanism is overtopping, followed by piping



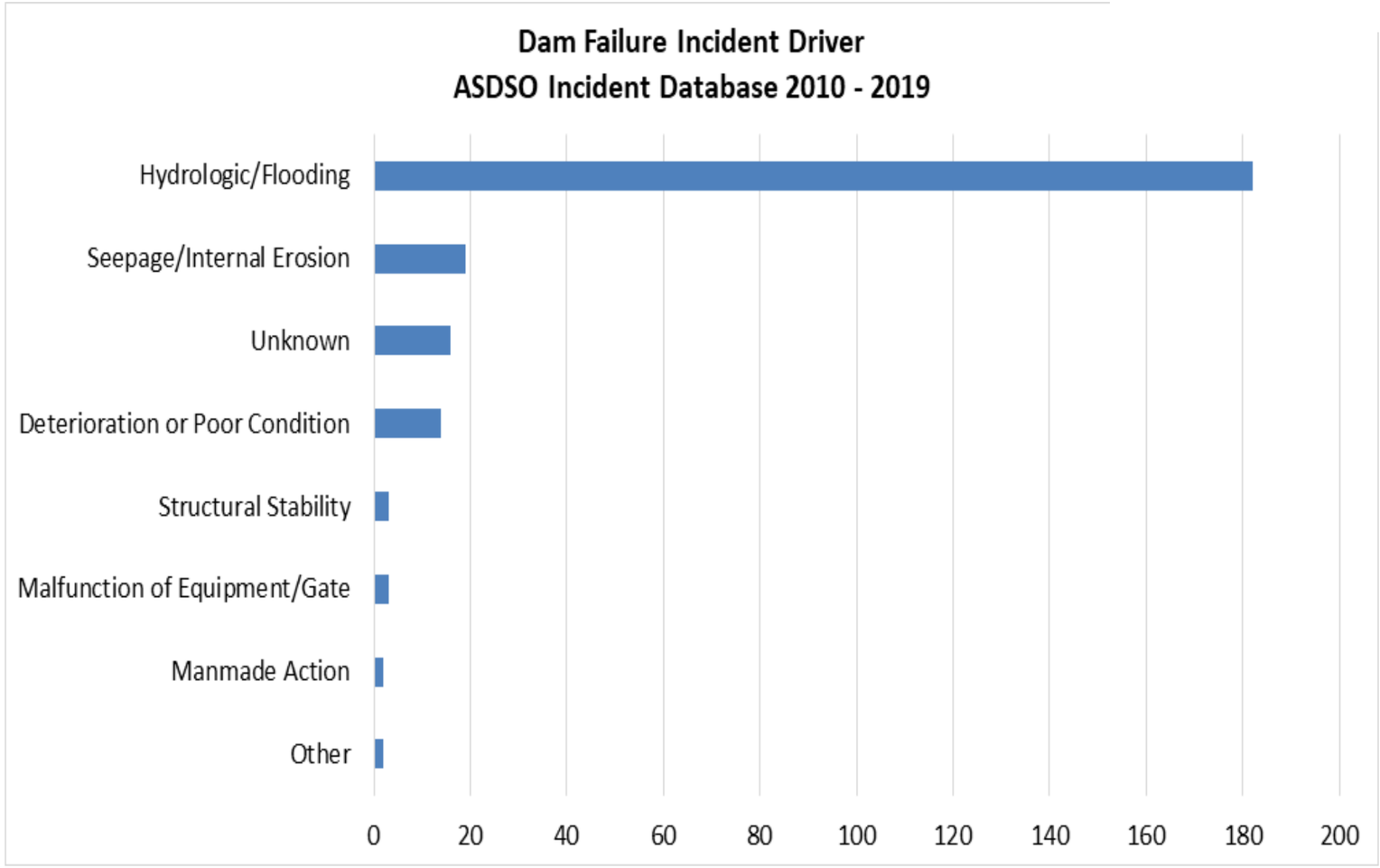
01 ADDRESS DAM RISK

DAM FAILURES

Amon causes, extreme meteorological events are by far the most relevant cause of dam failure

The reducing of returning period of such events due to the climate change may likely lead to an increase of dams' failure rate

Especially for aged dams, designed for underestimated returning periods



01 ADDRESS DAM RISK

RESUME

EXTREME EVENTS

The rise in intensity of extreme events observed in the last decades due to climate change may result in an increased probability of failure.



SMALL EARTH DAMS

Small earth dams are much more common than larger dams and are built and maintained with significantly lower safety standards.



IMPLICATIONS

Understanding the dam break phenomena, as well as the effects of distributed drag on the flow can lead to improved flood forecasting and adaptation measures.



02 RISK OF DAM FAILURE

How to quantify risk?

The Risk R related to a given event in this case a dam failure is give by:

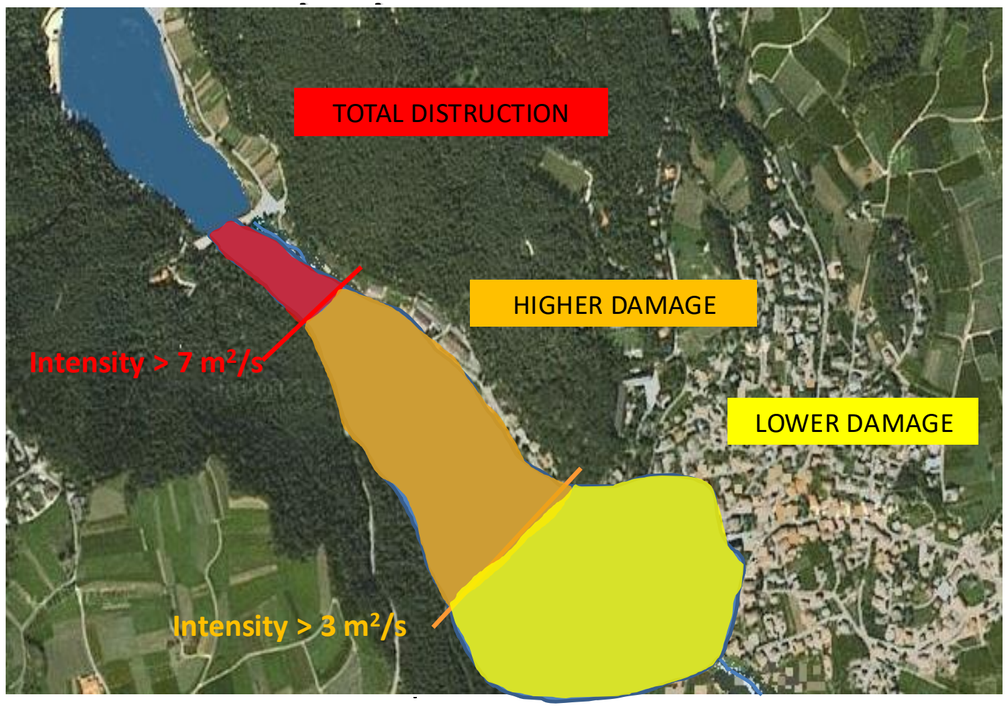
$$R=P*D*V$$

P – Probability that the event will occur.

D – Potential damage represent the total worth exposed to risk (private goods, activities, infrastructure, artistic and environmental patrimony).

V – Vulnerability is the share of D that will occur due to the event.

The Vulnerability, defined as the degree of loss produced by a given phenomenon. The rigorous estimation could be complex. In the case of dam-break simplified models relate V with local peak water depth and velocity.

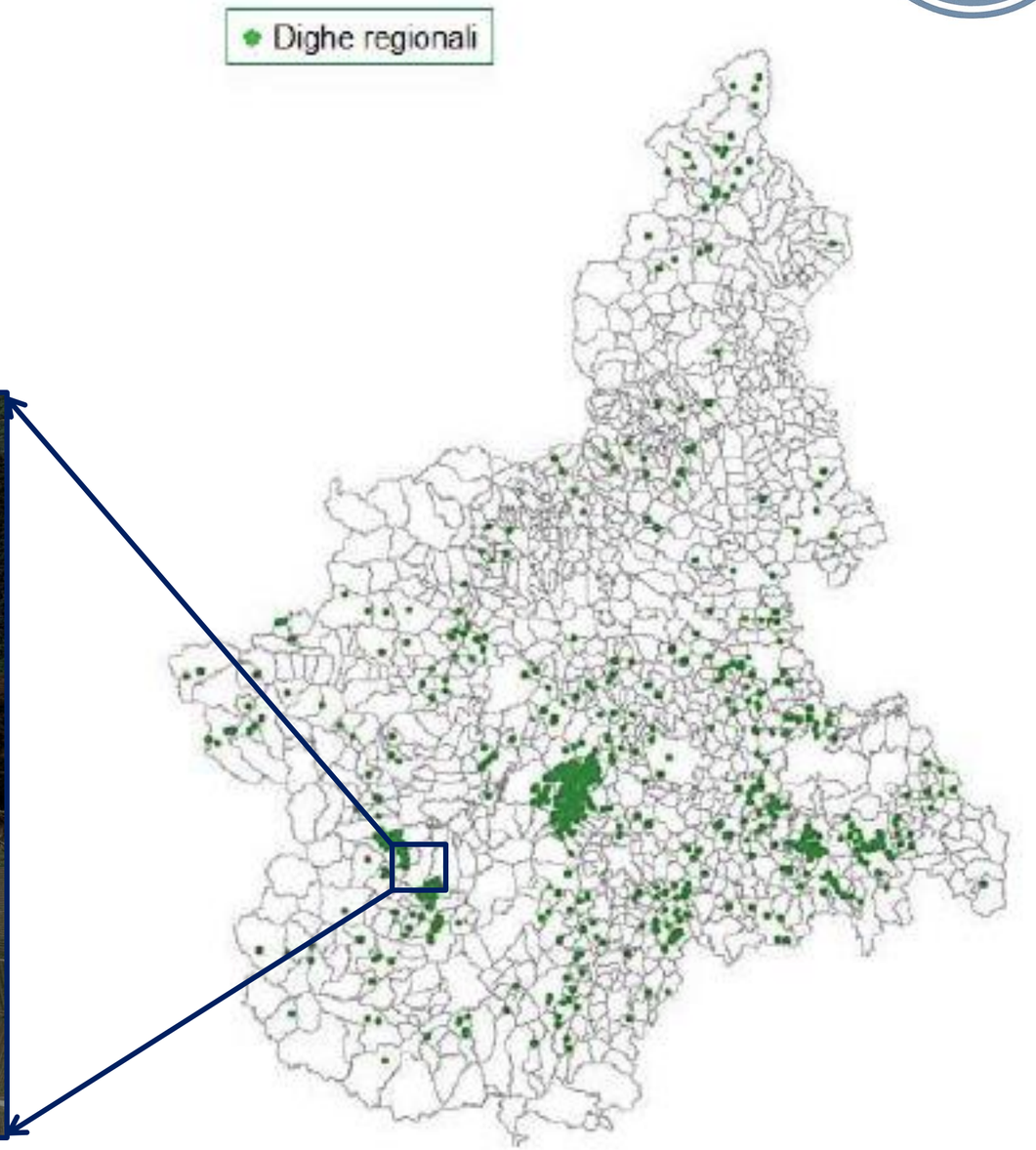


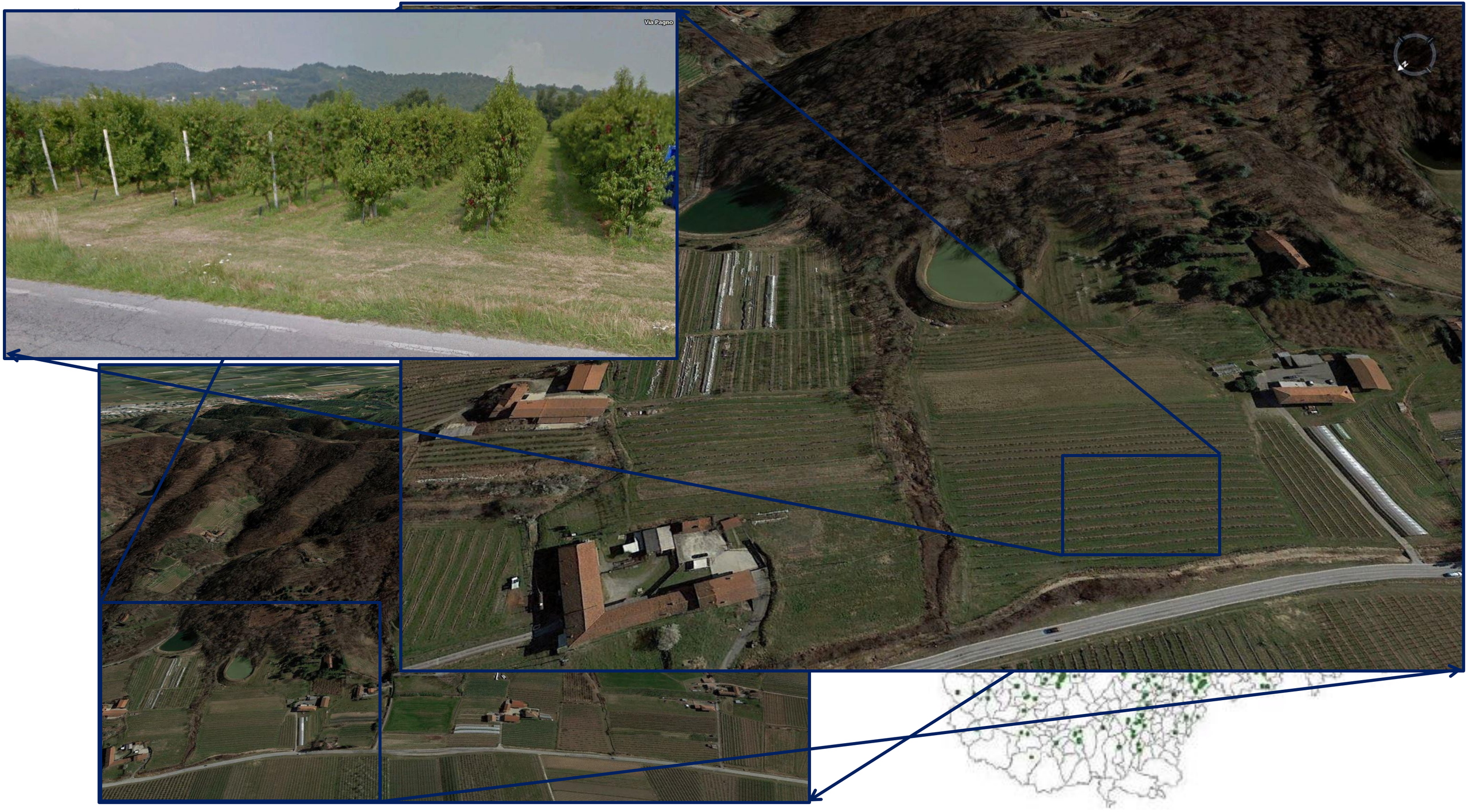
02 RISK OF DAM FAILURE

What's exposed to risk? The Piedmont case study

Let's focus on small dams

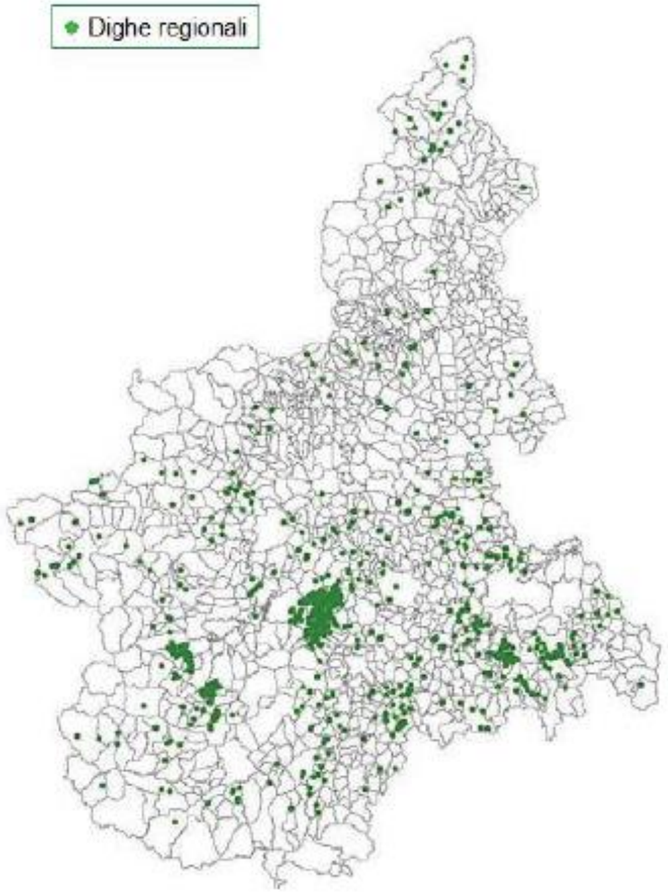





Via Pagno

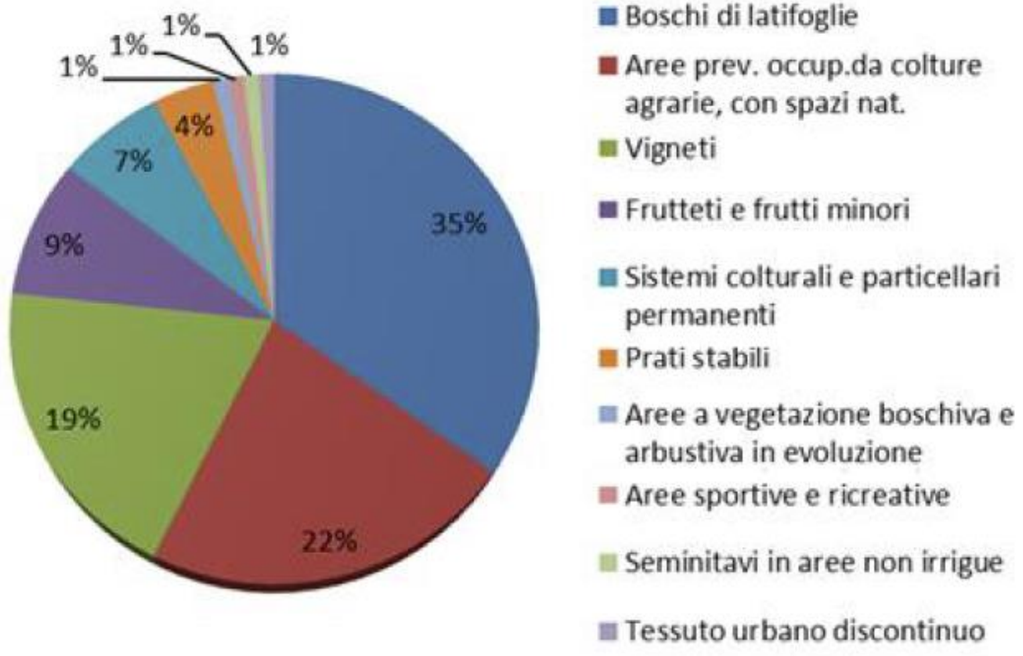
02 RISK OF DAM FAILURE

What's exposed to risk? The Piedmont case study



A land usage analysis for areas downstream 101 reservoirs in Cuneo and Torino's province reveal that most of floodable areas are characterized by:

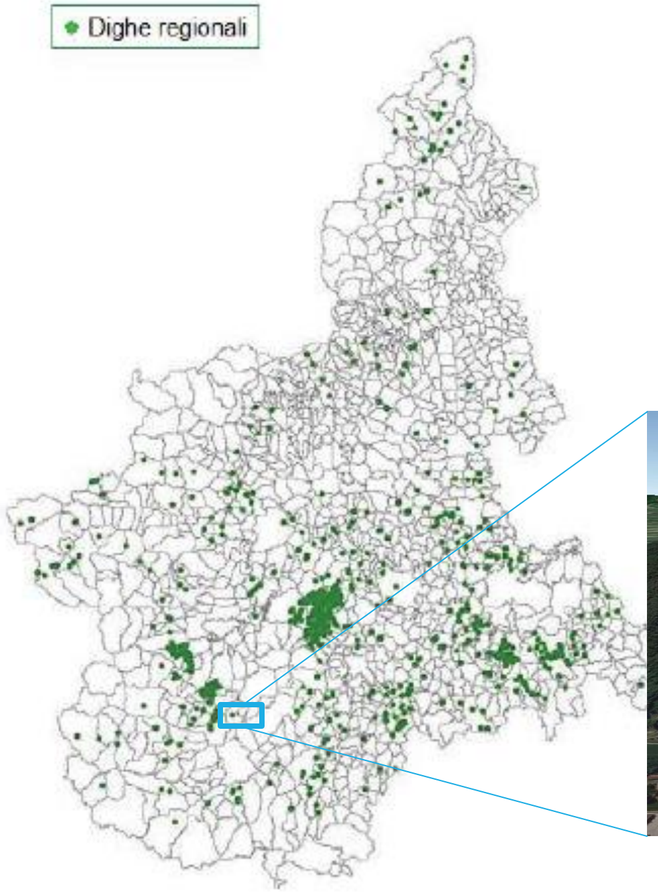
- Deciduous forests 35%
- Crops 22%
- Vineyards 19%
- Fruit trees 9%

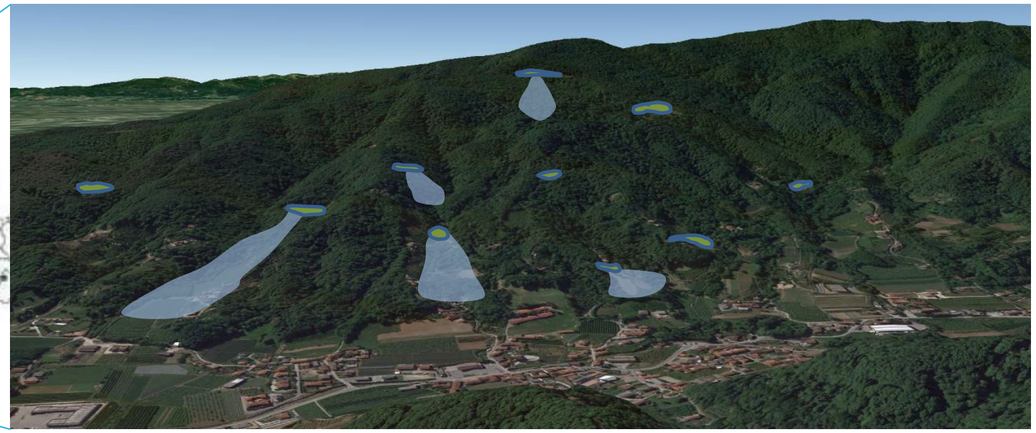


Most of land downstream reservoir are characterized by canopies of tall rigid vegetation, those kind of obstacles have a huge impact on wave propagation

02 RISK OF DAM FAILURE

What's exposed to risk? The Piedmont case study





RESUME

- Absence of tributary and outfall (no incised riverbeds)
- Severely rough surfaces (forests, vineyards, plantations)
- Limited affected area but high prevalence



03 MODELLING THE WAVE

How to model this odd roughness

A key parameter on dam break wave propagation is friction (friction slope or drag force per unit mass Sf)

$$S_f = n^2 h^{-\frac{4}{3}} U^2$$

Traditional channel flows are dominated by wall friction which derive form ground shear

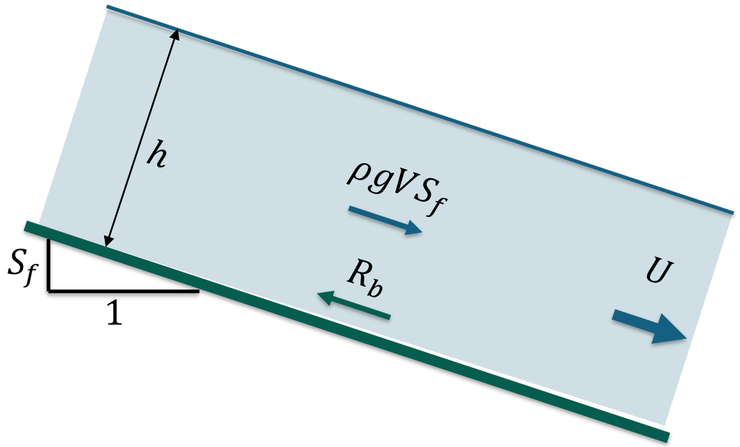
$$S_f = \frac{C_d m D}{2g(1-\phi_v)} U^2$$

When the friction caused by protruding obstacles (such as vegetation or buildings) there is both and ground shear total drag force on obstacles

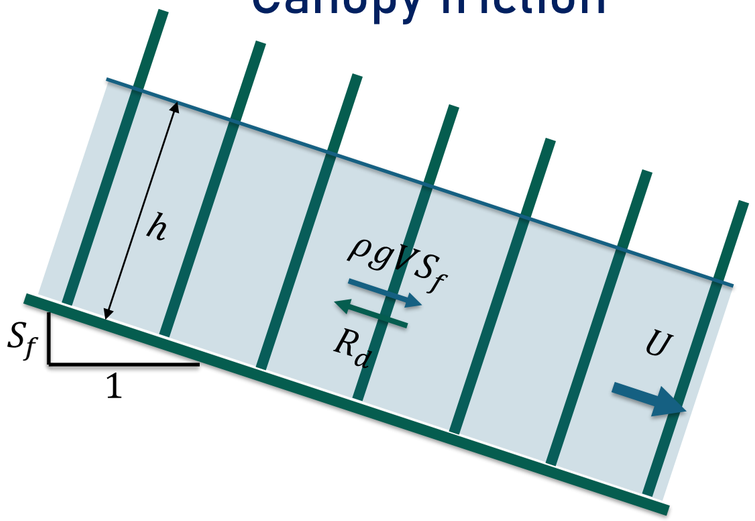
Manning equivalence

$$n = \sqrt{\frac{C_d m D}{2g(1-\phi_v)}} h^{\frac{2}{3}}$$

Wall friction



Canopy friction



03 MODELLING THE WAVE

How to quantify peak water depth and velocity?

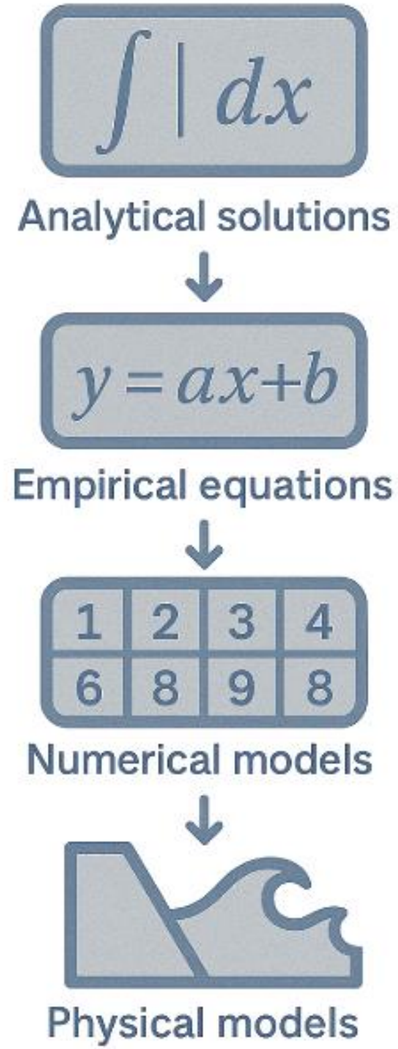
- Analytical solutions
- Empirical equations

→ Analytical solution apply to idealized condition, 2D wave with (Dressler 1950) or without friction (Ritter 1896) while empirical equations typically give few information such as peak discharge from the breach

- Numerical models
  - Depth averaged models (SWE) HECRAS
  - Full 3D models (CDF or SPH)

→ May be challenging model complex geometry or two-phase flows typical of dam break waves. Simplified numerical simulation require tailored parameters to model canopy friction, air entrainment or solid discharge.

- Physical Models → Provides benchmark solution from controlled environment fundamental for numerical models tuning



03 MODELLING THE WAVE

KNOWLEDGE GAP

3D WAVES

Most analytical solutions describe 2D dam break waves



CANOPY DRAG

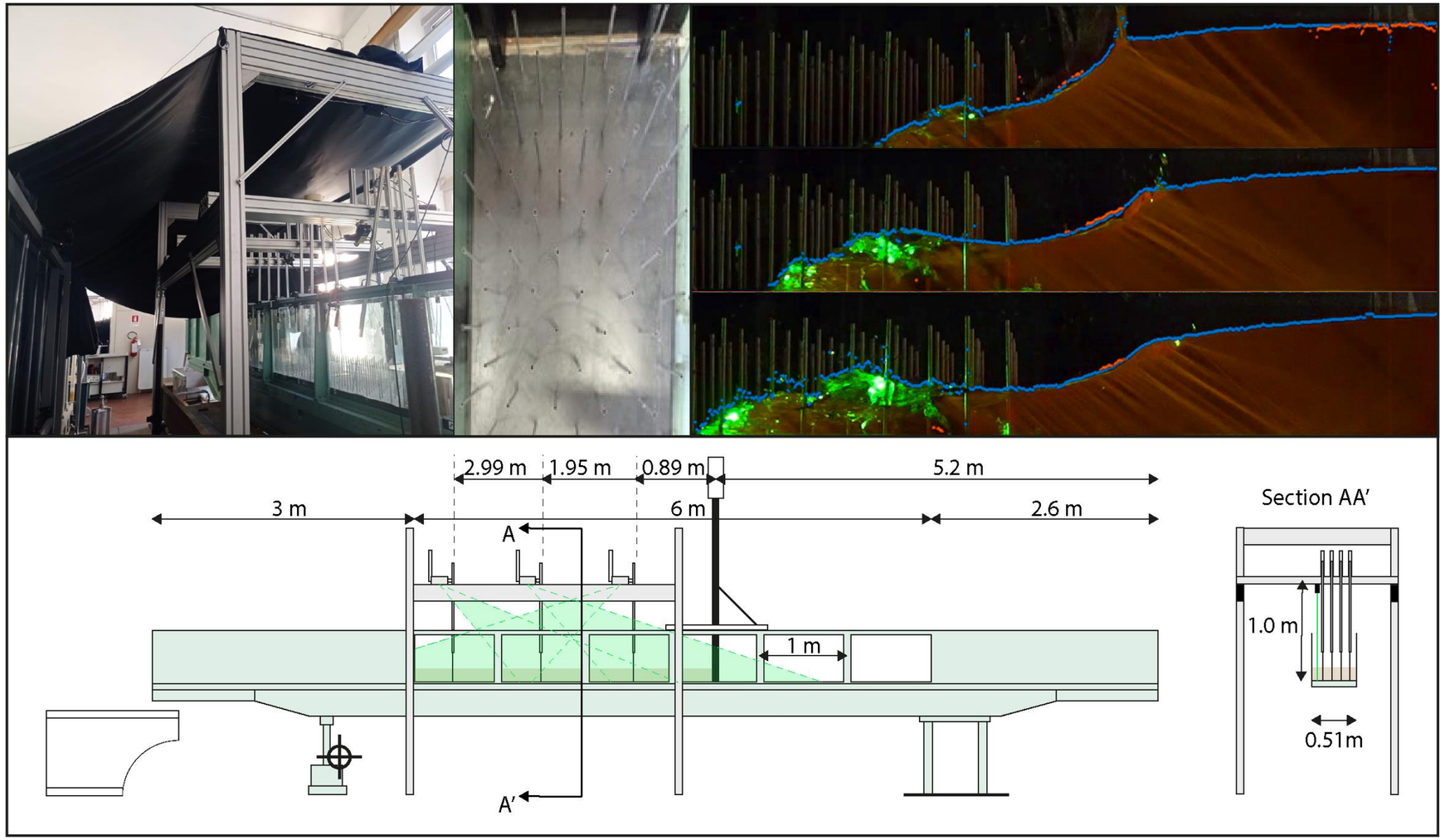
Most of the literature on dam break is focused on wall friction or isolated obstacles



03 PHISICAL MODELS

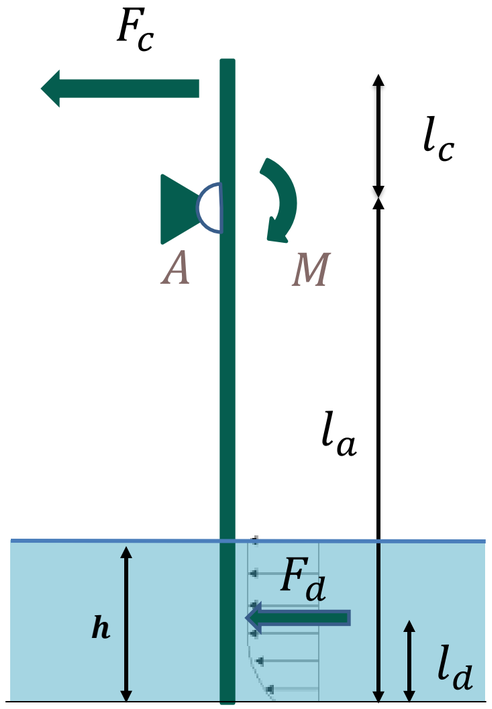
2D dam break wave on canopy drag

Physical experiments of dam break wave propagation on a prismatic channel covered by an array of rigid cylinders allow to investigate the effect of rigid emergent vegetation on wave propagation as well as control variable like terrain slope and initial water depth

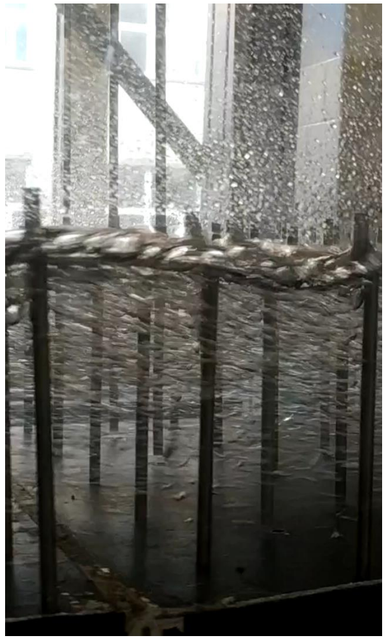


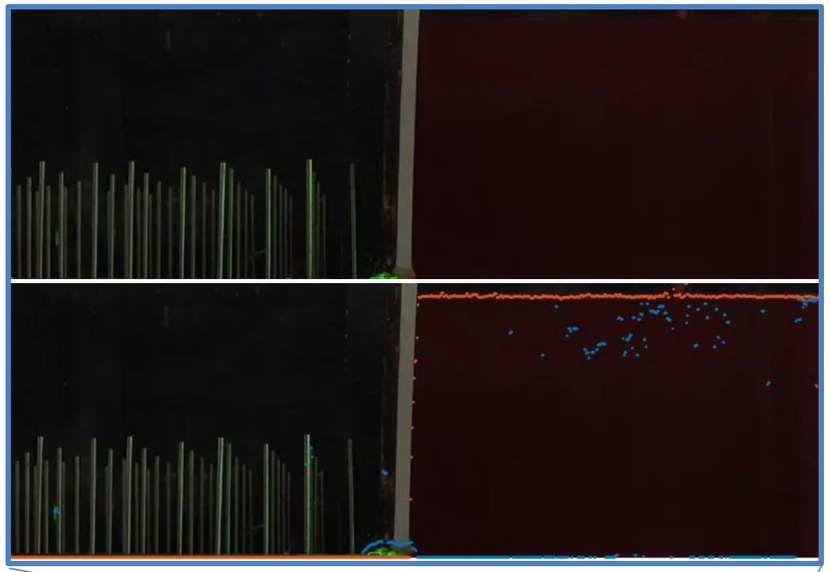
2D dam break wave on canopy drag

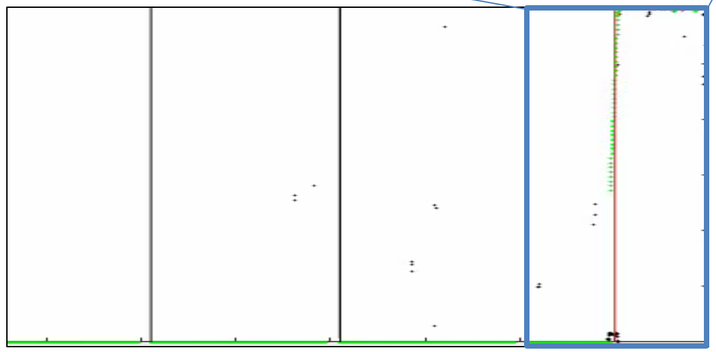
- Water depth detected with cameras
- Drag force measured with load cells









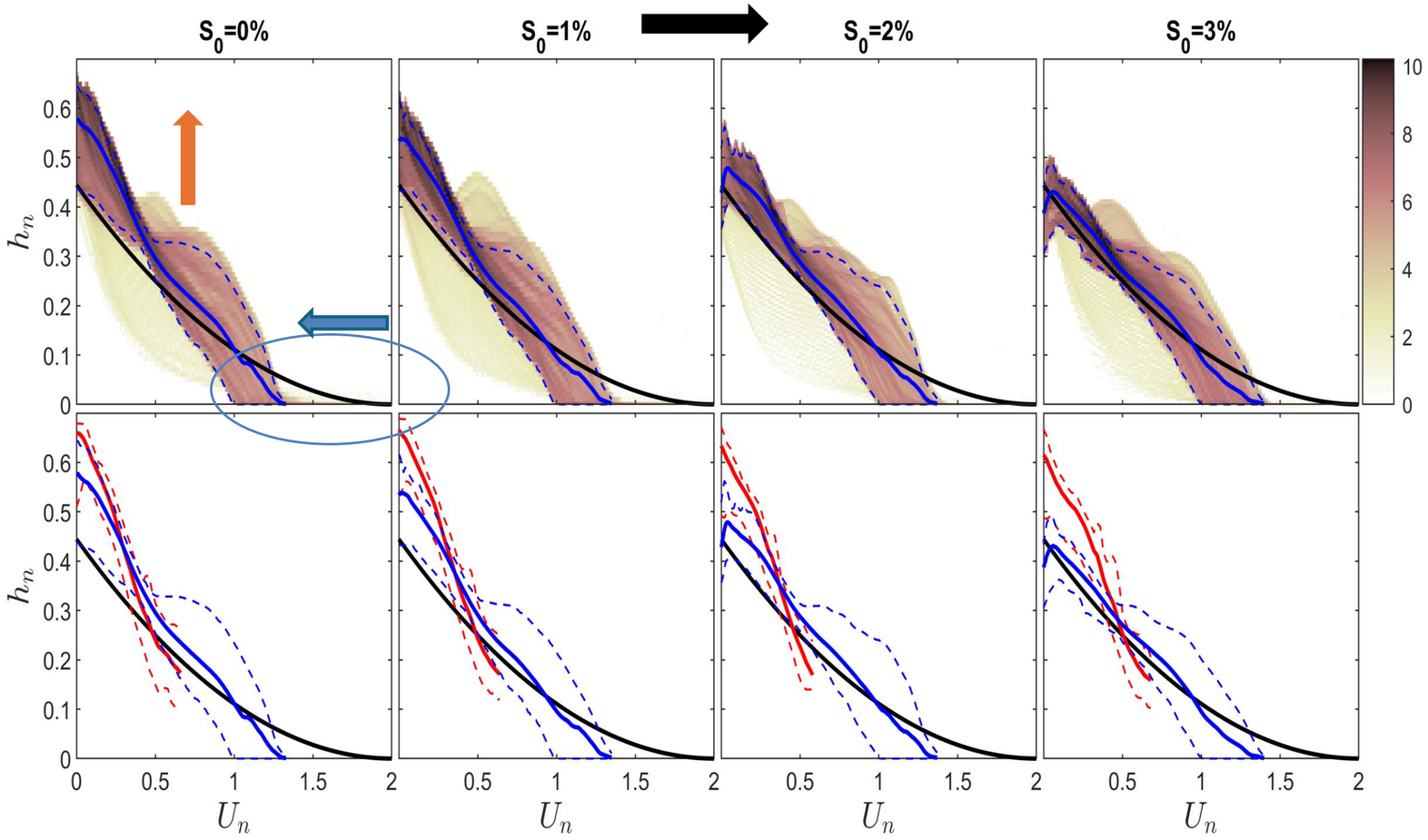


03 PHISICAL MODELS

2D dam break wave on canopy drag

The average canopy case wave (blue line) compared with analytical horizontal frictionless solution (black line) show significant reduction in front speed as a result of intense fiction as well as an increase of depth.

Present results from rod density $m = 194$ compared with $m = 1206$ (Melis et al 2020) sowing that this two mechanism are enhanced by increasing rod density



03 PHISICAL MODELS

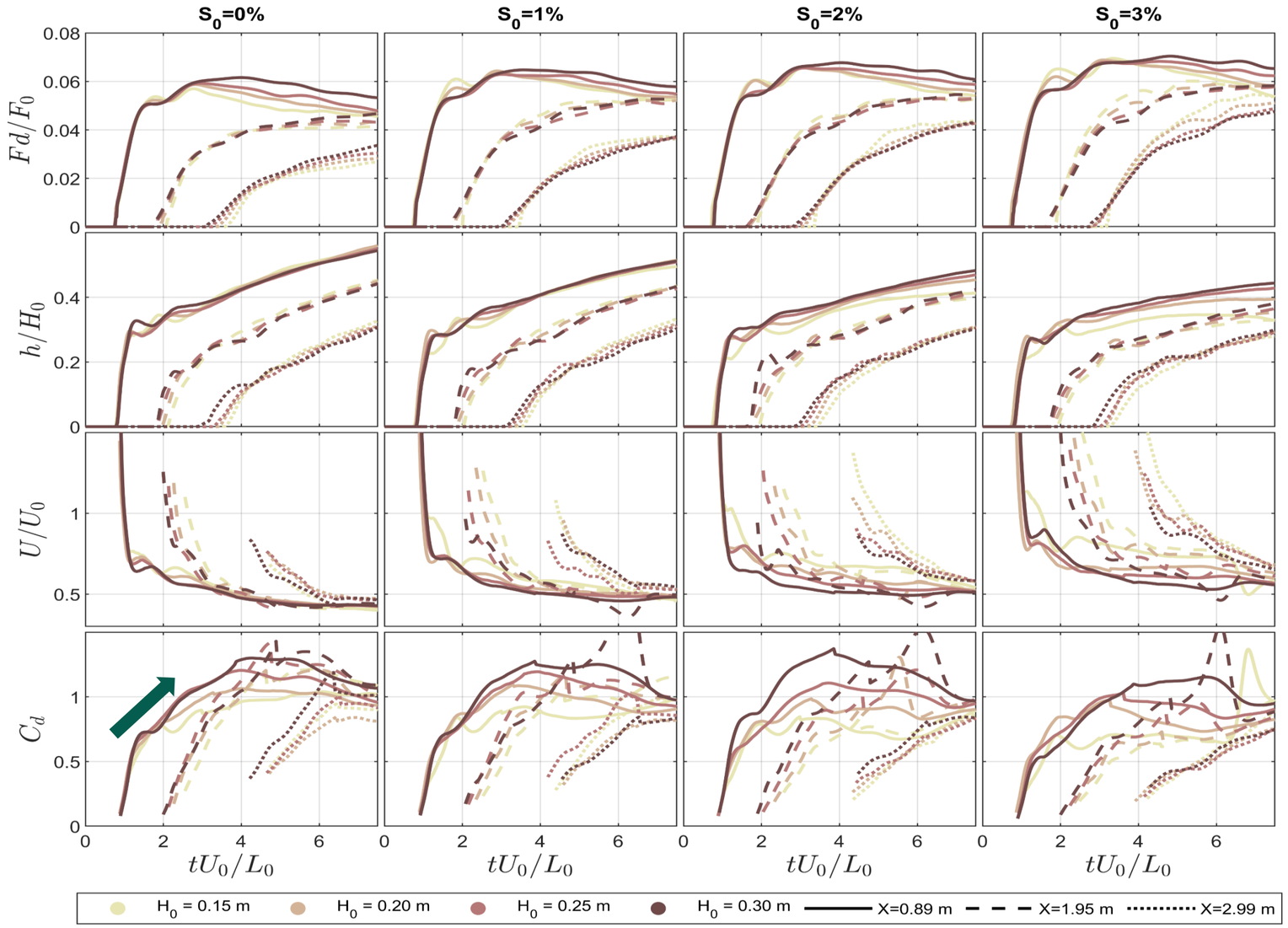
2D dam break wave on canopy drag

Trough the traditional definition of drag force rod's drag coefficient is derived from force measurements

$$C_d = \frac{2F_d}{\rho h D U^2}$$

In the tip region the drag coefficient resulted to be significantly lower than the isolated cylinder case.

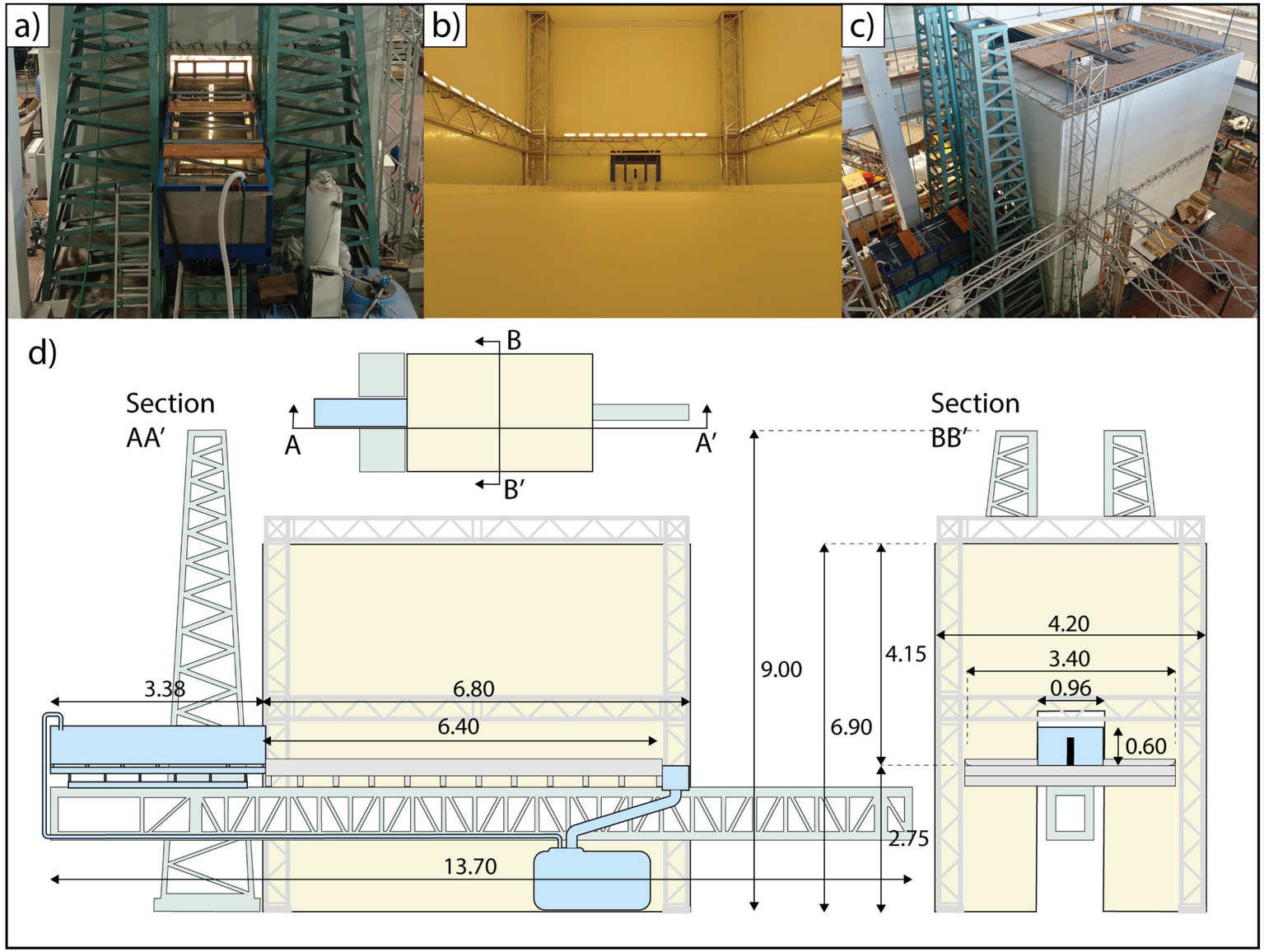
Result confirmed by Cd as can be derived from depth measurements



03 PHISICAL MODELS

3D dam break wave on canopy drag

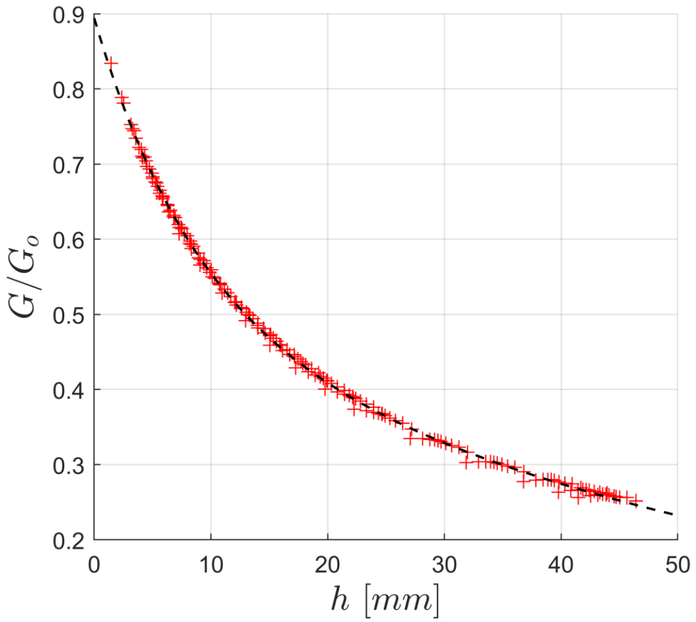
Physical experiments of dam break wave propagation on wide planar surfaces allow investigate fully 3D wave with no lateral constrains as in real world scenario. Explore the effect of canopy like roughness for wave expanding over floodplains reveal flow redistribution mechanism resulting from anisotropy of obstacles arrangement



03 PHISICAL MODELS

3D dam break wave on canopy drag

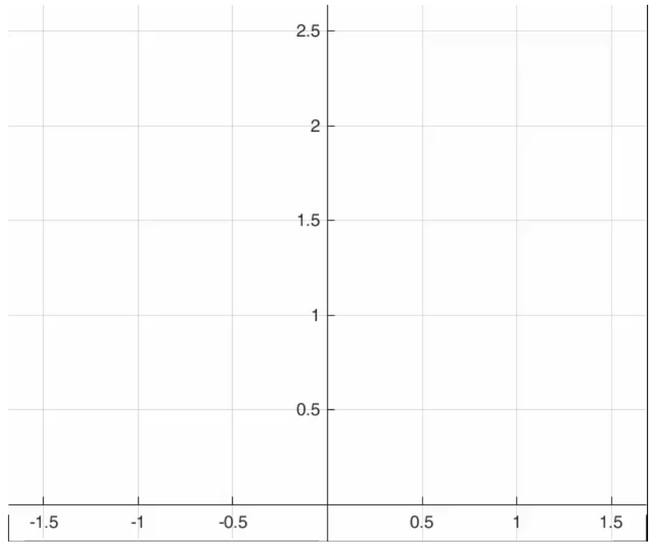
- Water depth detected with cameras matching depth with light attenuation

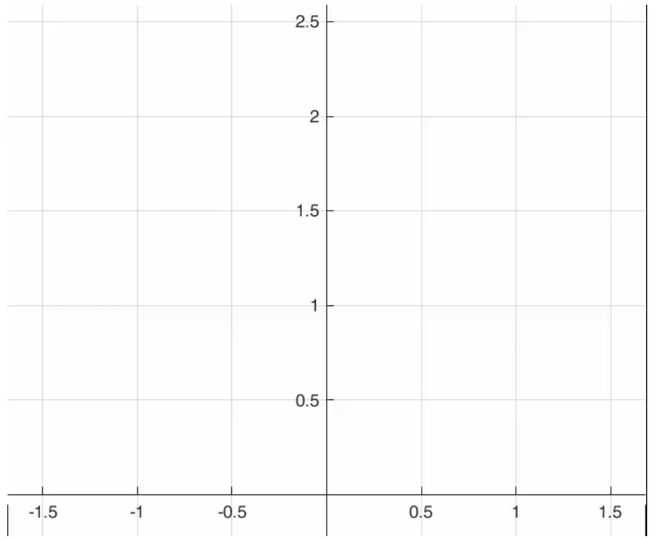


SMOOTH CASE

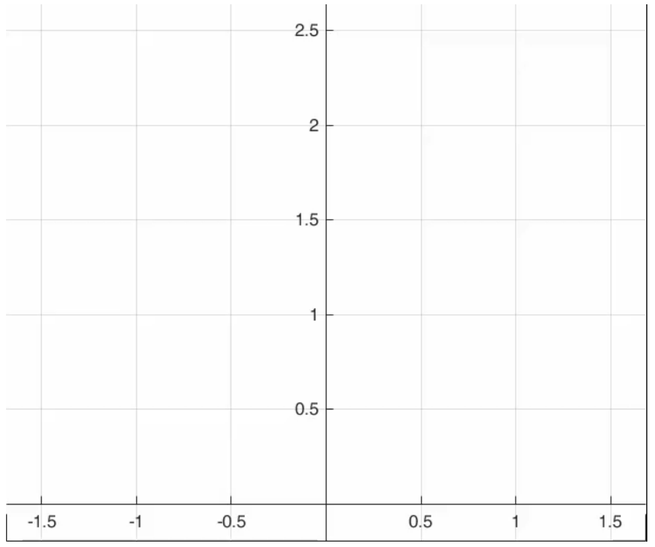
CANOPY CASE

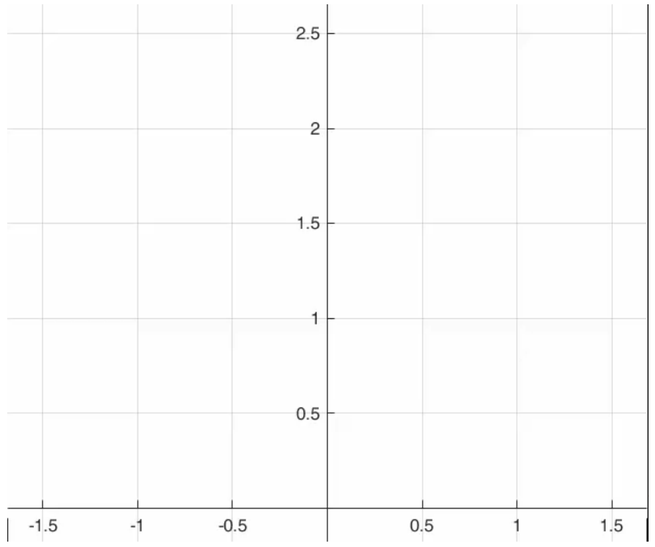
20 cm





30 cm





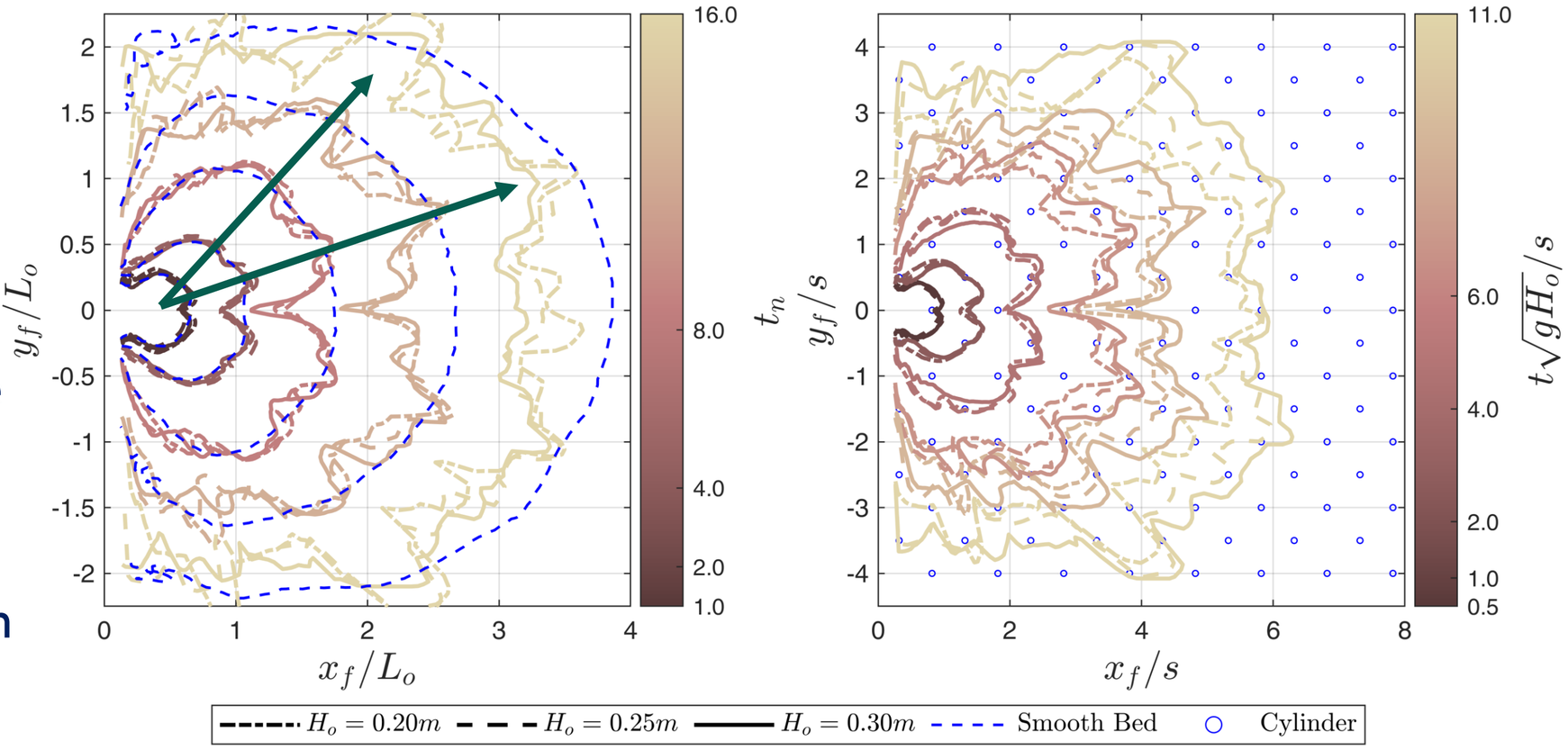
03 PHISICAL MODELS

3D dam break wave on canopy drag

Regular canopy generate a typical leaf shaped wave compared to the smooth case (blue dashed line).

Overall results in a reduction of wave front velocity accordingly with the 2D case.

Although for some directions flow redistribution among minor drag path lead a slight front's speed up.



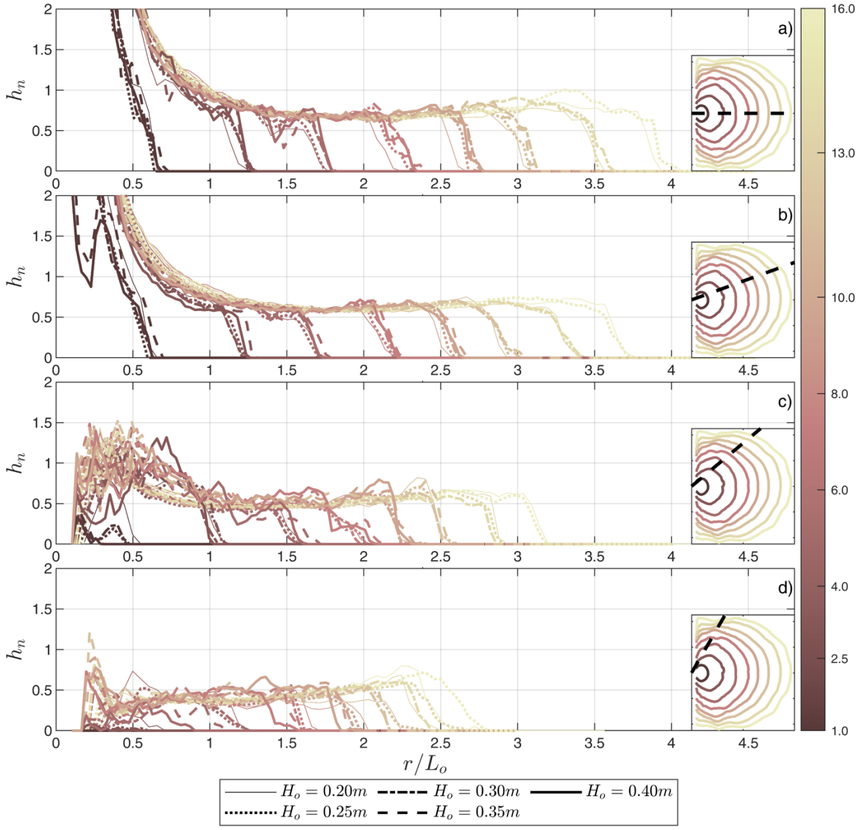
03 PHISICAL MODELS

3D dam break wave on canopy drag

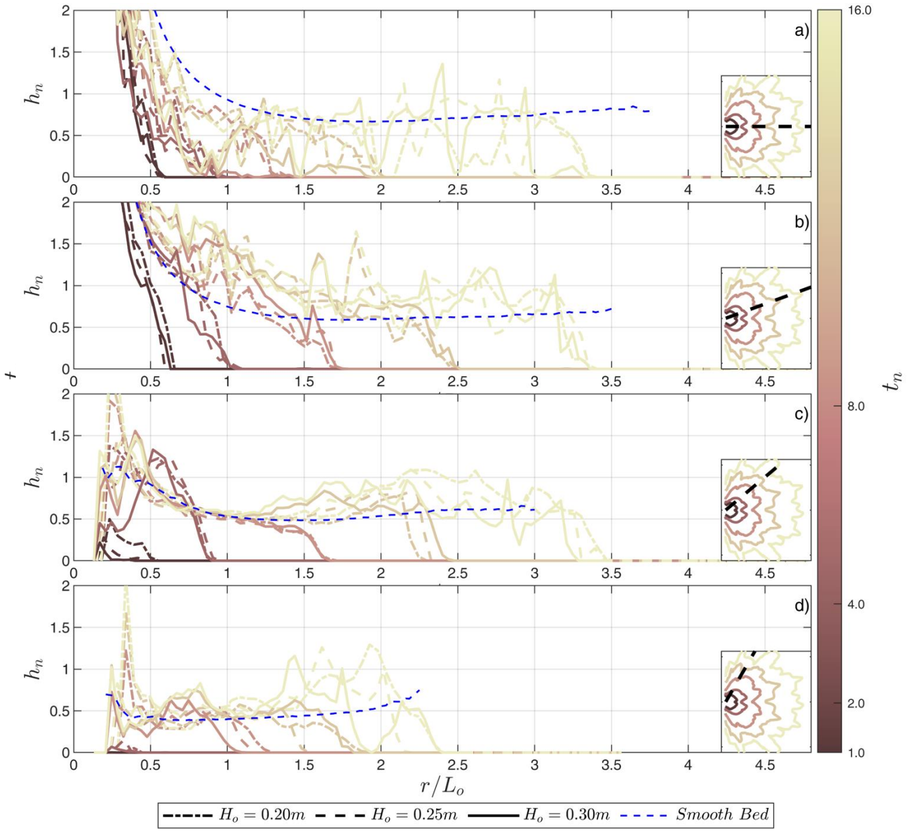
Vertical section of the wave revealed an almost constant water depth far from the breach for the smooth bad case (left figure)

In the canopy case (right figure) the water depth compared with smooth case averaged free surface (dashed blue line) exhibit general higher water depth with a more significant spatial variability.

SMOOTH CASE



CANOPY CASE



Thanks for the attention

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