Tailings Dam Breach Analysis (TDBA)

University of Alberta Geotechnical Grad Seminar

March 1, 2023

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Land Acknowledgement

- *Edmonton is located within Treaty 6 Territory and within the Métis homelands and Métis Nation of Alberta Region 4. We acknowledge this land as the traditional territories of many First Nations such as the Nehiyaw (Cree), Denesuliné (Dene), Nakota Sioux (Stoney), Anishinaabe (Saulteaux) and Niitsitapi (Blackfoot).*

- *Calgary is located within Treaty 7 Territory and within the homeland of the Northwest Metis and Metis Nation of Alberta Region 3. We acknowledge that the land by which we do our work as the traditional territories of several First Nations peoples including the Siksika, Piikani, Kainai, Tsuut'ina, and Stoney Nakoda (comprised of the Chiniki, Bearspaw, and Wesley First Nations).*

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Topics to Be Discussed

i. The "why" of TDBA
ii. What Are Tailings?! Properties and Rheology
iii. TDBA Background
iv. Failure Modes and Scenarios
v. TDB Process
vi. Tailings Release Volume
vii. Breach Modelling
viii. Downstream Routing
ix. Recommendations and On-going Research

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The “why” of TDBA

- Definition: A tailings dam failure is defined as a physical breach of the dam followed by uncontrolled and typically sudden release of any or all stored materials.
- Critical to informing dam consequence classification
- Inform Emergency Response Plan (ERP) and Emergency Preparedness Plan (EPP) which are regulatory requirements in Alberta (and many other jurisdictions)

Mount Polley; image source: canadianconsultingengineer.com

What Are Tailings?!

- In the most basic sense tailings are the waste product produced from the processing of mined ores
- The properties of these tailings can vary dramatically
- The properties of the tailings are further varied by the depositional environment

Image source: Simms, 2016

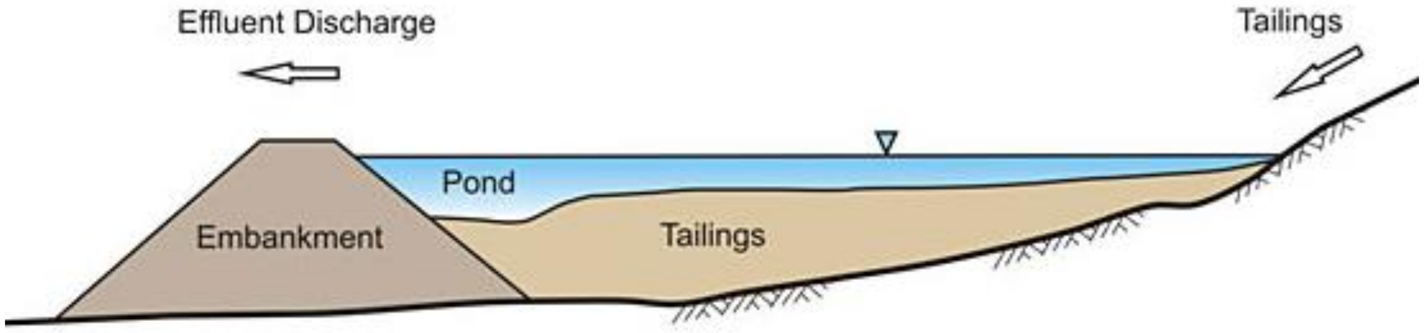

Image source: GARD guide, Ch. 6

Tailings Characterization and Liquefaction Potential

- Robust geotechnical investigations to determine the composition and characteristics of a tailings deposit are critical for TSF design, operations, and more
- Potential of tailings to undergo flow liquefaction is critical to TDBA
- A general rule is saturated tailings that exhibit contractive behaviour under shear should be assumed to experience flow liquefaction

Image source:
gahag.net

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So it flows - Rheology

- Tailings exist in the complex realm between soil mechanics and fluid mechanics
- If liquefaction occurs, what is the likely behaviour of the now fluid-like tailings in the case of a containment breach?
  - Materials such as tailings can exhibit complex non-Newtonian flow behaviours
  - Behaviour may not be consistent between initial mobilization and runout
  - Adequate rheological characterization of these tailings deposits is critical to inform any TDBA

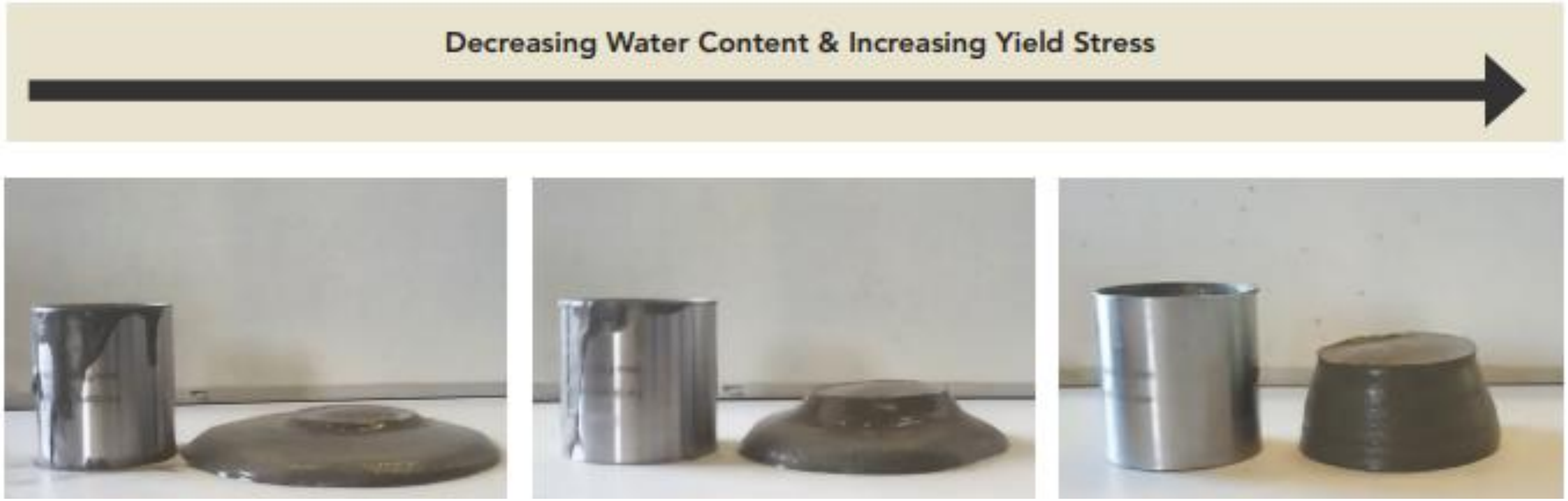

Image Source: CDA

Further Considerations

- Liquefaction potential can change dramatically as a result of the initial dam failure
- Tailings rheology is incredibly complex
- A model is only as good as its inputs

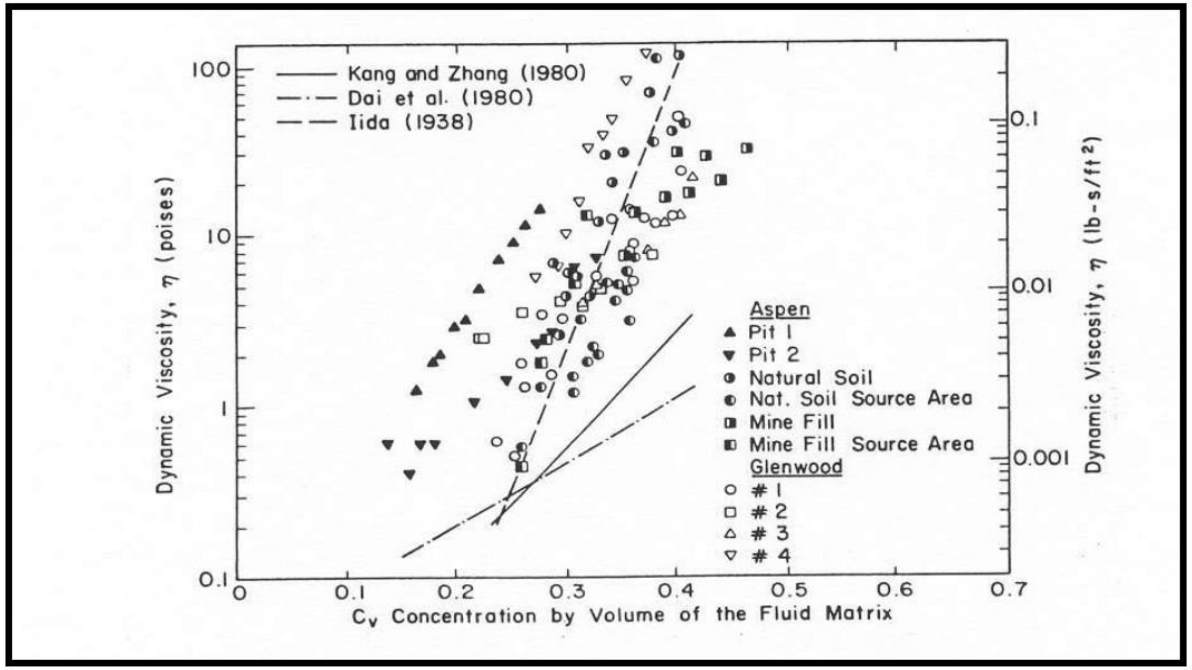

Figure 42. Dynamic Viscosity of Mudflow Samples versus Volumetric Concentration

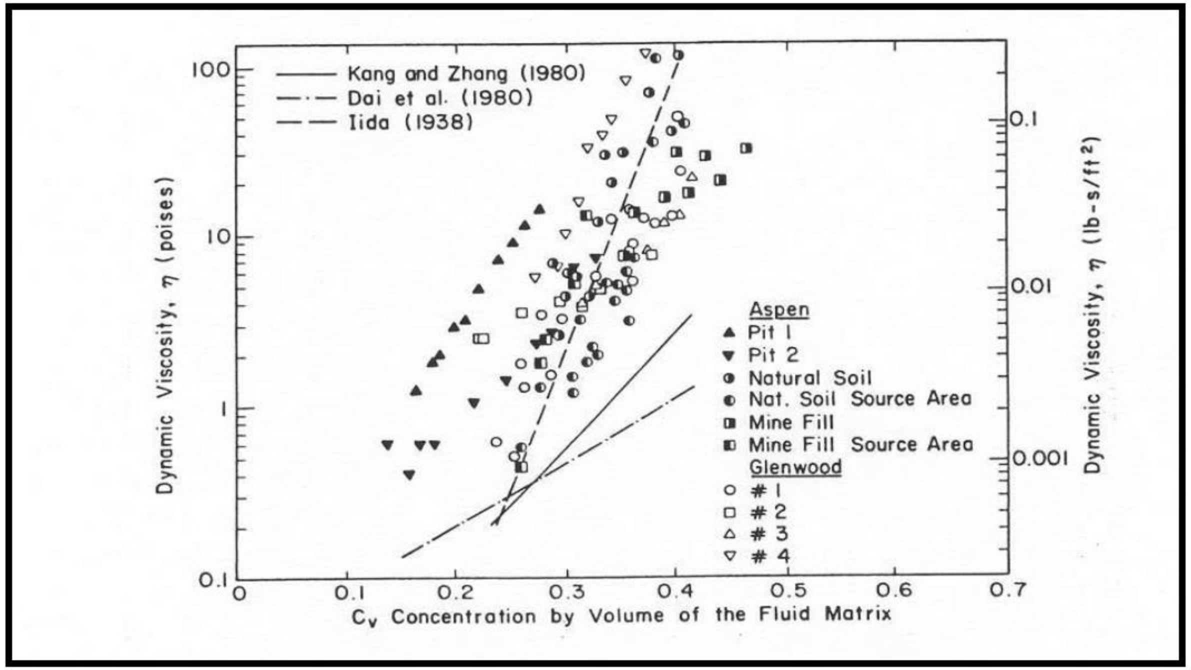

Figure 42. Dynamic Viscosity of Mudflow Samples versus Volumetric Concentration

Image source: FLO-2D Reference Manual

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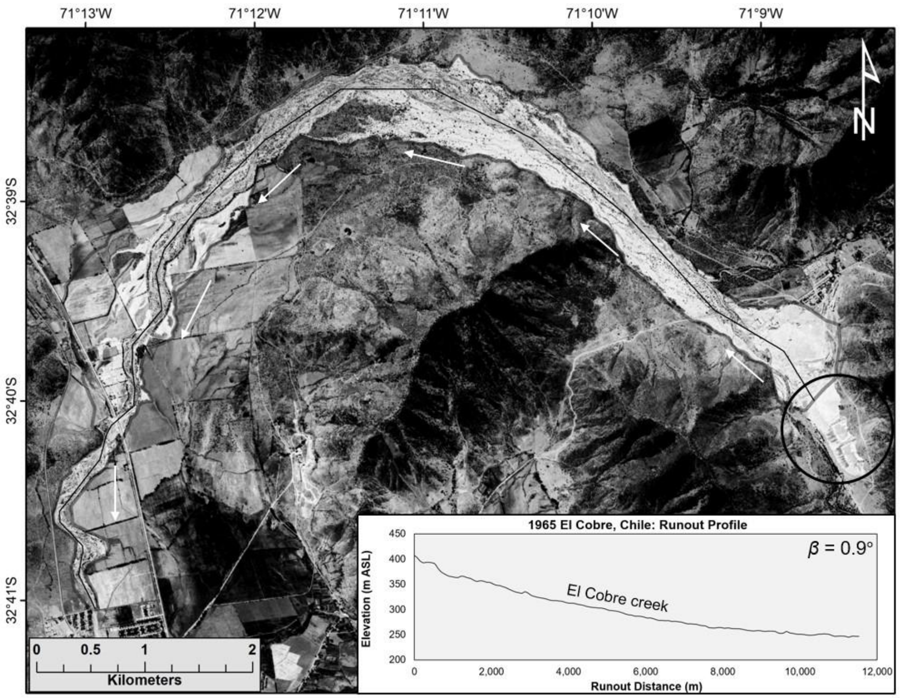
TDBA Background

- 1962 China, Huogudu, 3.3 Mm^3 of tailings, 171 fatalities
- 1965 Chile, El Cobre, 0.35 Mm^3 of tailings, 200 fatalities
- 1972 US, Buffalo Creek, WV, 0.5 Mm^3 of tailings, 125 fatalities
- 1985, Italy, Strava, 0.2 Mm^3 of tailings, 268 fatalities
- 2008, China, Toashi, 0.19 Mm^3 of tailings, 277 fatalities
- 2019, Brazil, Brumadinho, 12 Mm^3 of tailings, 267 fatalities



Useful links:

Chronology of tailings dam failures: WISE Uranium Project

A comprehensive global database of tailings flows (CanBreach): CanBreach Research Data Base

TDBA Background (Cont'd)

2019, Brazil, Brumadinho, 12 Mm^3 of tailings, 267 fatalities

https://www.youtube.com/watch?v=sKZUZQytads

Useful links:

Planet Lab Daily Earth Data: Planet Lab

Location: Córrego de Feijão mine, Brumadinho, Minas Gerais, Brazil
Date: 2019, Jan. 25
Ore: Iron
Incident: Tailings dam #1 failure
Estimated Release Volume: 12 Mm^3
Impacts: The tailings wave devastated the mine's loading station, its administrative area, and two smaller sediment retention basins (B4 and B4A); it then traveled approx. 7 km downhill until reaching Rio Paraopeba, thereby destroying a bridge of the mine's railway branch, and spreading to parts of the local community Vila Ferteco, near the town of Brumadinho; the slurry was then carried further by Rio Paraopeba; 267 people were killed, and several are still reported missing.
Planet© Imagery Date: 2019, Jan. 29

TDBA Background (Cont'd)

Image Source: Mining2Me

TDBA Background (Cont'd)

- No longer just a regulatory box to be checked
- The guidelines for TDBA are just coming out
- In 2021, the Canadian Dam Association (CDA) published the first bulletin for TDBA
- A short section in "Tailings Management Handbook – A lifecycle approach", in 2022 by SME

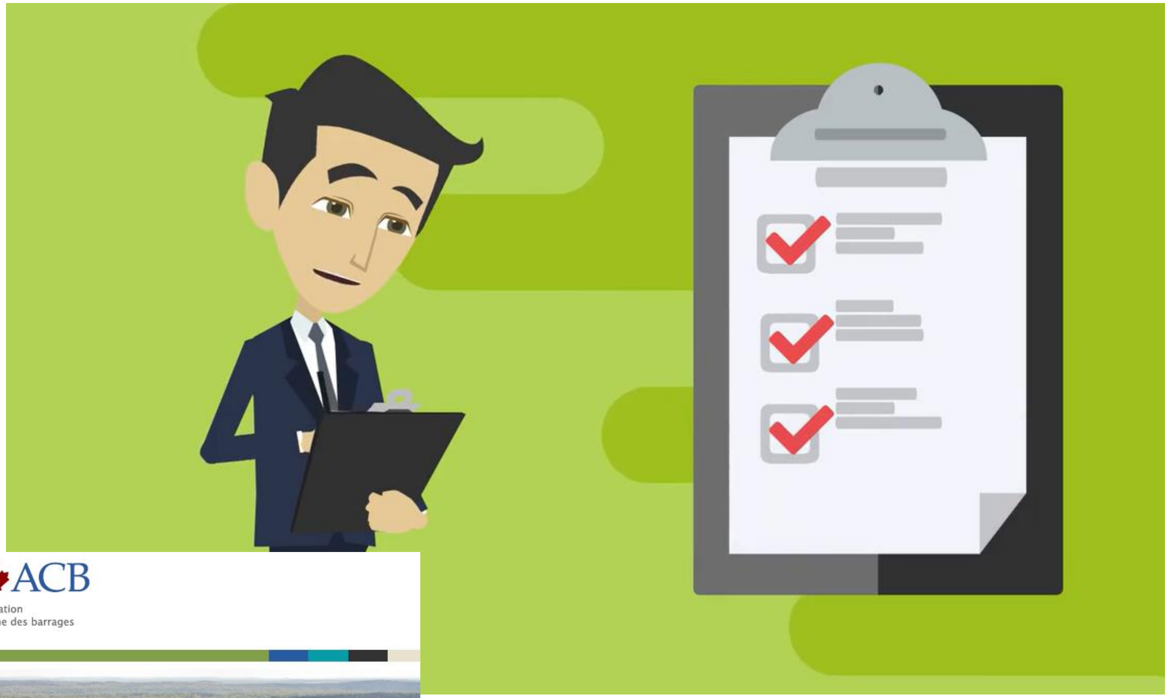
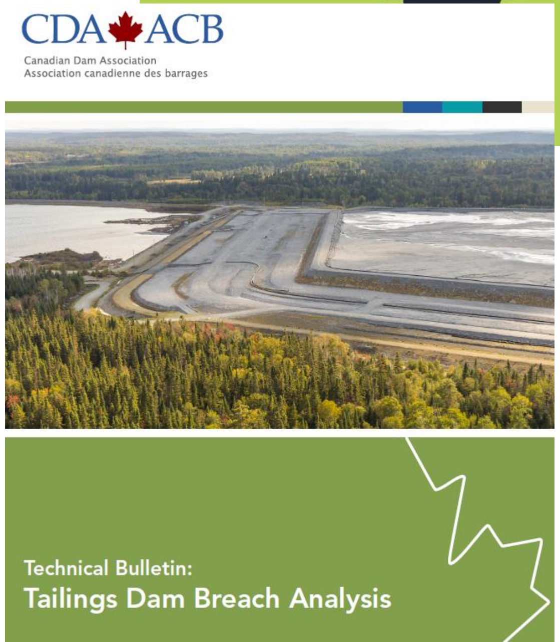


Image Source: Mining2Me



CDA ACB
Canadian Dam Association
Association canadienne des barrages

Technical Bulletin:
Tailings Dam Breach Analysis

Image Source: CDA

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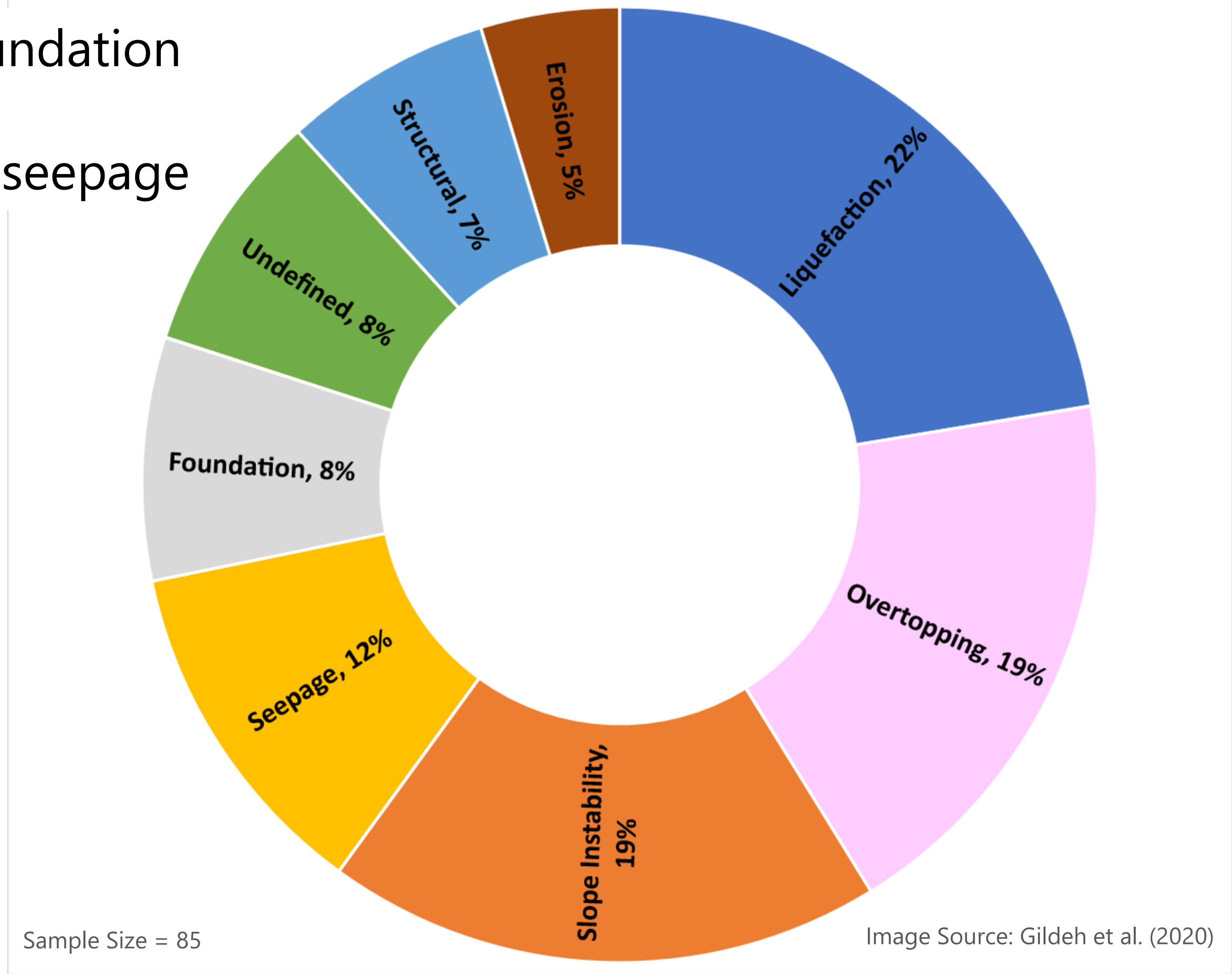
Failure Modes and Scenarios

- Collapse of foundation
- Overtopping
- Contaminated seepage



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Failure Modes and Scenarios (Cont'd)

Two common hydrologic conditions

- Fair weather (aka sunny-day)
- Flood induced (aka wet-/rainy-day)

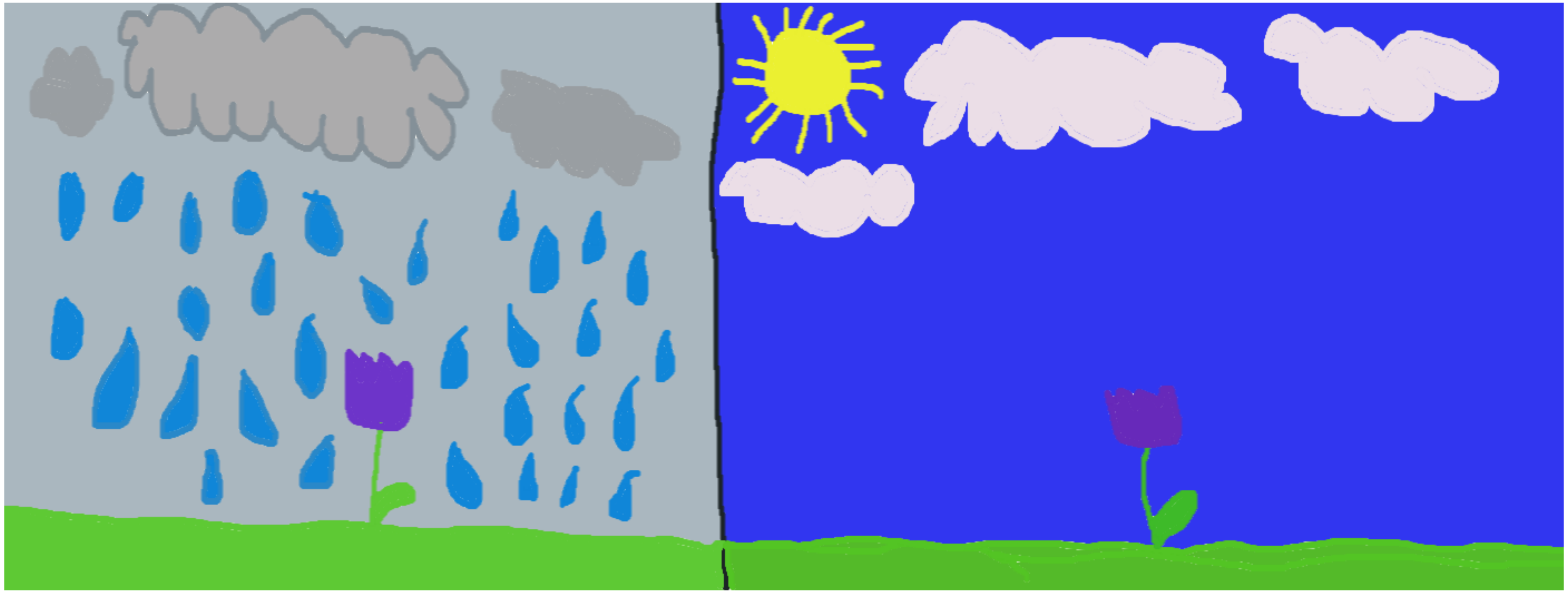

Image Source: deviantart

TDB Process

What is specific to tailings dam failures (compared to water retaining dams)

- Mobilization of tailings
- Runout characteristics (i.e., hyper-concentrated or mud/debris flows)
- Breach shape and dimensions can be very different

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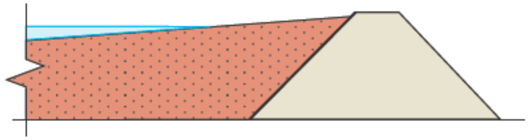
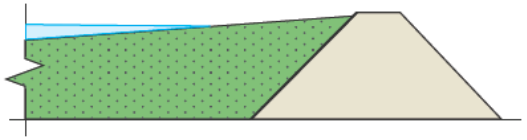
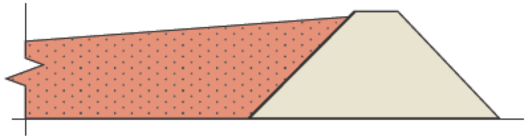
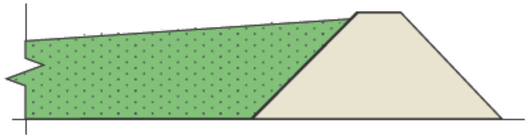
TDB Process (Cont'd)

- Tailings dam breach processes are <u>complex and not fully understood</u>
- Can be assumed as two processes
  - Process I: Discharge of the supernatant pond that carries eroded tailings and dam fill materials
  - Process II: Discharge of flowable tailings due to tailings liquefaction or progressive slumping of unsupported tailings

Supernatant pond present or pond release possible during breach	Potential for tailings runout as a result of flow liquefaction[1]	
	Yes	No
Yes	**Case 1A — Liquefiable Tailings with a Supernatant Pond:** Dam breach with flow of fluids, eroded tailings, and liquefied flowable tailings 	**Case 1B — Non-Liquefiable Tailings with a Supernatant Pond:** Dam breach with flow of fluids and eroded tailings, and tailings slumping due to retrogression of the unsupported tailings 
No	**Case 2A — Liquefiable Tailings without a Supernatant Pond:** Dam breach with liquefied flowable tailings only 	**Case 2B — Non-Liquefiable Tailings without a Supernatant Pond:** Slumping failure, or flow slide resulting from a slope failure 

Liquefiable Tailings | Non-Liquefiable Tailings | Supernatant Pond (Water, Fluid Tailings, etc.) | Tailings Dam

Notes:

1. Regardless of the failure mode, the flow liquefaction referred to in this figure is related to the flow potential of tailings after the dam is breached.

Image Source: CDA

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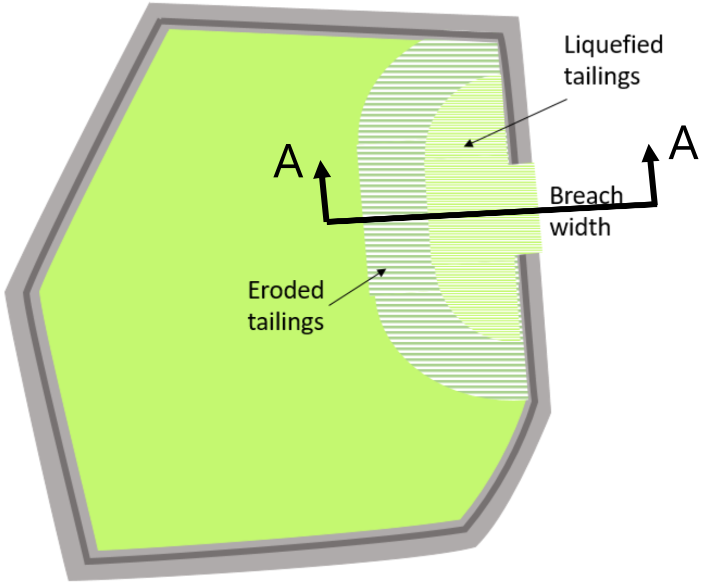
TDB Process (Cont’d)

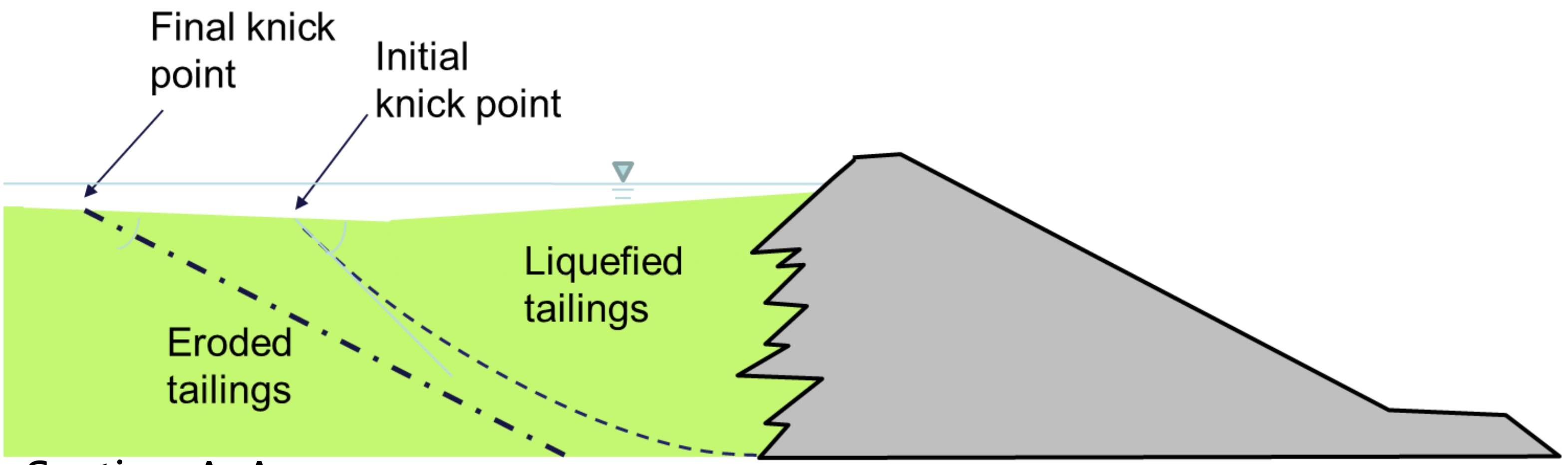
- If the volume of supernatant pond is relatively high, one could use Process I for estimating the mobilized tailings and total volume of runout.
- If there is no supernatant pond, or the pond is very small, or the pond is away from the dam, one may use Process II for estimating the mobilized tailings and total volume of runout.
- An alternative approach would be to combine the estimated total volume of tailings solids and water released during the breach to characterize a single sediment-water mixture for the entire breach outflow hydrograph.

Image Source: Adobe Stock

Tailings Release Volume Estimate

- A geotechnical analysis to determine if the tailings could liquefy (the trigger for tailings liquefaction is the dam failure)
- Estimate the <u>volume of liquefied tailings</u> from:
  - *breach geometry*
  - *basin geometry*
  - *geotechnical data and analysis*
- Estimate the <u>volume of eroded tailings</u> based on:
  - *the volume of supernatant pond*
  - *basin geometry*
  - *geotechnical data*





Section A-A

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Tailings Release Volume Estimate (Cont'd) – Liquefaction Failure

Tailings Release Volume Estimate (Cont'd)

- Other simplified methods are available!
  - *Statistical regression (e.g., Rico et al., 2008; Larrauri and Lall, 2018; etc.)*

- Flowability approximation (Fontaine and Martin, 2015)

Mine Water and the Environment
https://doi.org/10.1007/s10230-020-00718-2

TECHNICAL ARTICLE

Tailings Dam Breach Analysis: A Review of Methods, Practices, and Uncertainties

Hossein Kheirkhah Gildeh[1] · Alexandra Halliday[2] · Alfredo Arenas[2] · Hua Zhang[1]

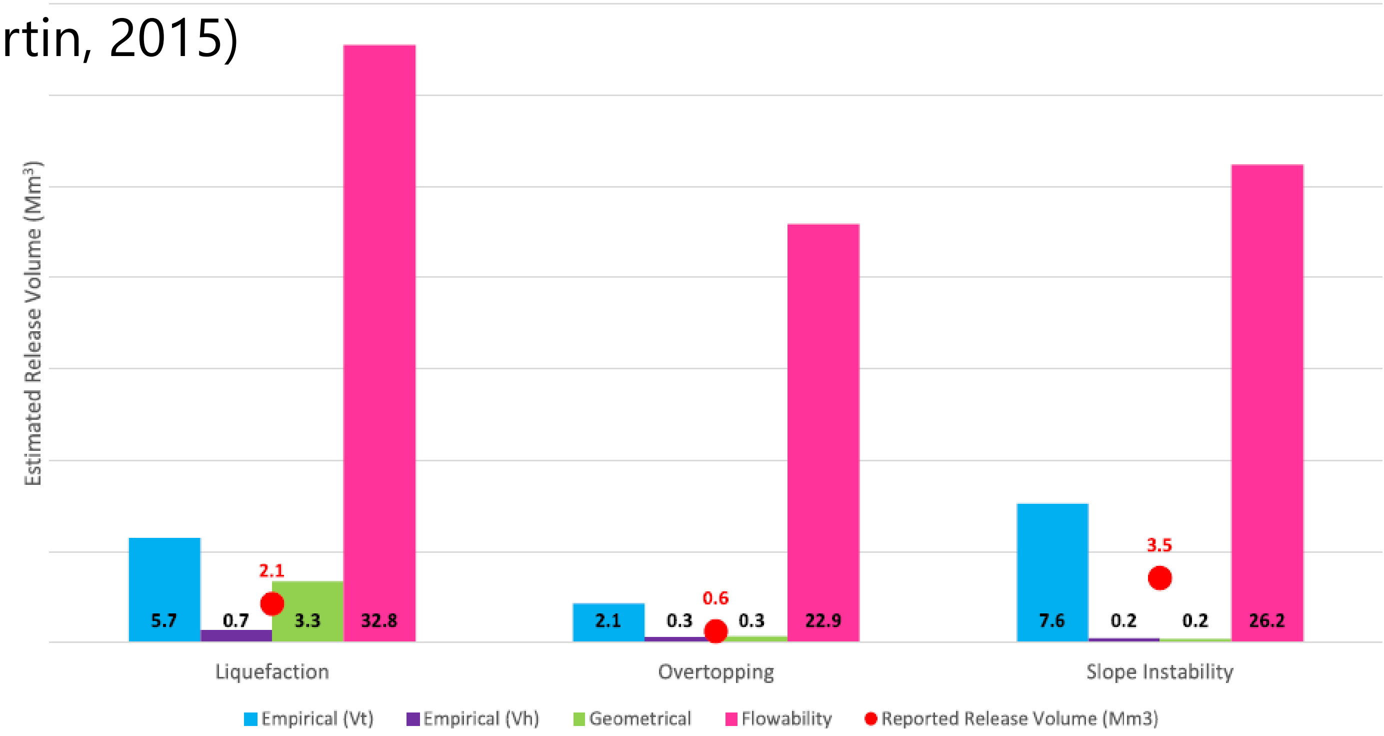

Fig. 4 Release volume by method and failure mechanism

Useful links:

Gildeh et al. (2020): Paper on TDBA

Image Source: Gildeh et al. (2020)

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Breach Modelling

- Breach modelling will identify the shape of the breach hydrograph and its peak
- Breach prediction methods for earthen dams
  - parametric models
  - semi-physically based models
  - physically based models

Useful links:

West et al. (2018): Breach Prediction Paper

A guide to breach prediction

M. West[1], M. Morris[2] and M. Hassan[3]

[1] Student, University of Surrey, [2] Senior Consultant, HR Wallingford, [3] Senior Engineer, HR Wallingford
Editor: Craig Goff, HR Wallingford, c.goff@hrwallingford.com

Parametric Model	Time to Failure, t_f (hr)	Average breach width, $\bar{B}$ (m)	Side Slopes, z $(h:v)$	Peak Outflow, Q_p (m^3/s)	Number of Case Studies
Froehlich (1995a, 1995b)	$t_f = 0.00254 V_w^{0.53} h_b^{-0.9}$	$\bar{B} = 0.1803 k_0 V_w^{0.32} h_b^{0.19}$ $k_0 = \begin{cases} 1.4 & OT \\ 1.0 & P \end{cases}$	$z = \begin{cases} 1.4 & OT \\ 0.9 & P \end{cases}$	$Q_p = 0.607 V_w^{0.295} h_w^{1.24}$	1995a: 22, 1995b: 63
Walder & O'Connor (1997)				$Q_p = a(h_w V_w)^b$ where: $a, b = \begin{cases} 0.99, 0.40 & Landslide \\ 0.61, 0.43 & Constructed \\ 0.19, 0.47 & Moraine \end{cases}$	
Froehlich (2008)	$t_f = 0.0176 \sqrt{\frac{V_w}{g h_b^2}}$	$\bar{B} = 0.27 k_0 V_w^{\frac{1}{3}}$ Where: $k_0 = \begin{cases} 1.3 & OT \\ 1.0 & P \end{cases}$	$z = \begin{cases} 1.0 & OT \\ 0.7 & P \end{cases}$		74
Xu & Zhang (2009)	$\frac{t_f}{t_r} = C_5 \left(\frac{h_d}{h_r}\right)^{0.654} \left(\frac{V_w^{1/3}}{h_w}\right)^{1.246}$ where: $C_5 = b_5$ $b_5 = \begin{cases} 0.038 & HE \\ 0.066 & ME \\ 0.205 & LE \end{cases}$	$\frac{\bar{B}}{h_b} = 5.543 \left(\frac{V_w^{1/3}}{h_w}\right)^{0.739} e^{C_3}$ where: $C_3 = b_4 + b_5$ $b_4 = \begin{cases} -1.207 & OT \\ -1.747 & P \end{cases}$ $b_5 = \begin{cases} -0.613 & HE \\ -1.073 & ME \\ -1.268 & LE \end{cases}$	1	$\frac{Q_p}{\sqrt{g V_w^{5/3}}} = 0.133 \left(\frac{V_w^{1/3}}{h_w}\right)^{-1.276} e^{C_4}$ where: $C_4 = b_4 + b_5$ $b_4 = \begin{cases} -0.788 & OT \\ -1.232 & P \end{cases}$ $b_5 = \begin{cases} -0.089 & HE \\ -0.498 & ME \\ -1.433 & LE \end{cases}$	75
Pierce at al. (2010)				$Q_p = 0.0176 (V_w h_w)^{0.606}$ $Q_p = 0.038 (V_w^{0.475} h_w^{1.09})$	87
Froehlich (2016a, b)	$t_f = 60 \sqrt{\frac{V_w}{g h_b^2}}$	$\bar{B} = 0.23 k_0 V_w^{\frac{1}{3}}$ Where:	$z = \begin{cases} 1.0 & OT \\ 0.6 & P \end{cases}$	$Q_p = 0.0175 k_0 k_H \sqrt{\frac{g V_w h_w h_b^2}{\bar{W}}}$ Where:	2016a: 111, 2016b: 41

Breach Modelling (Cont'd)

- Comparison 1: Two Semi-Physically Based Models vs One Parametric Model

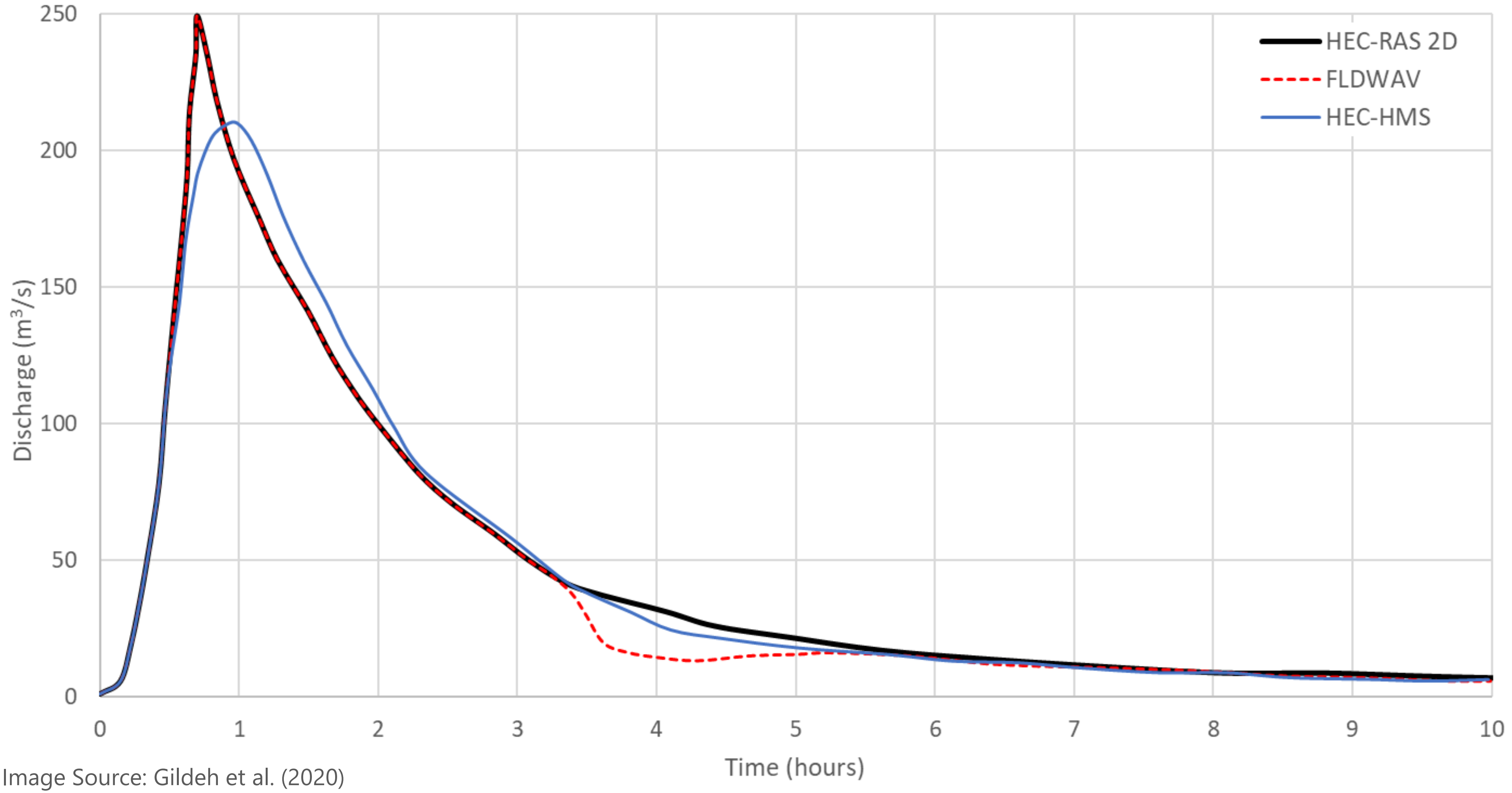

Image Source: Gildeh et al. (2020)

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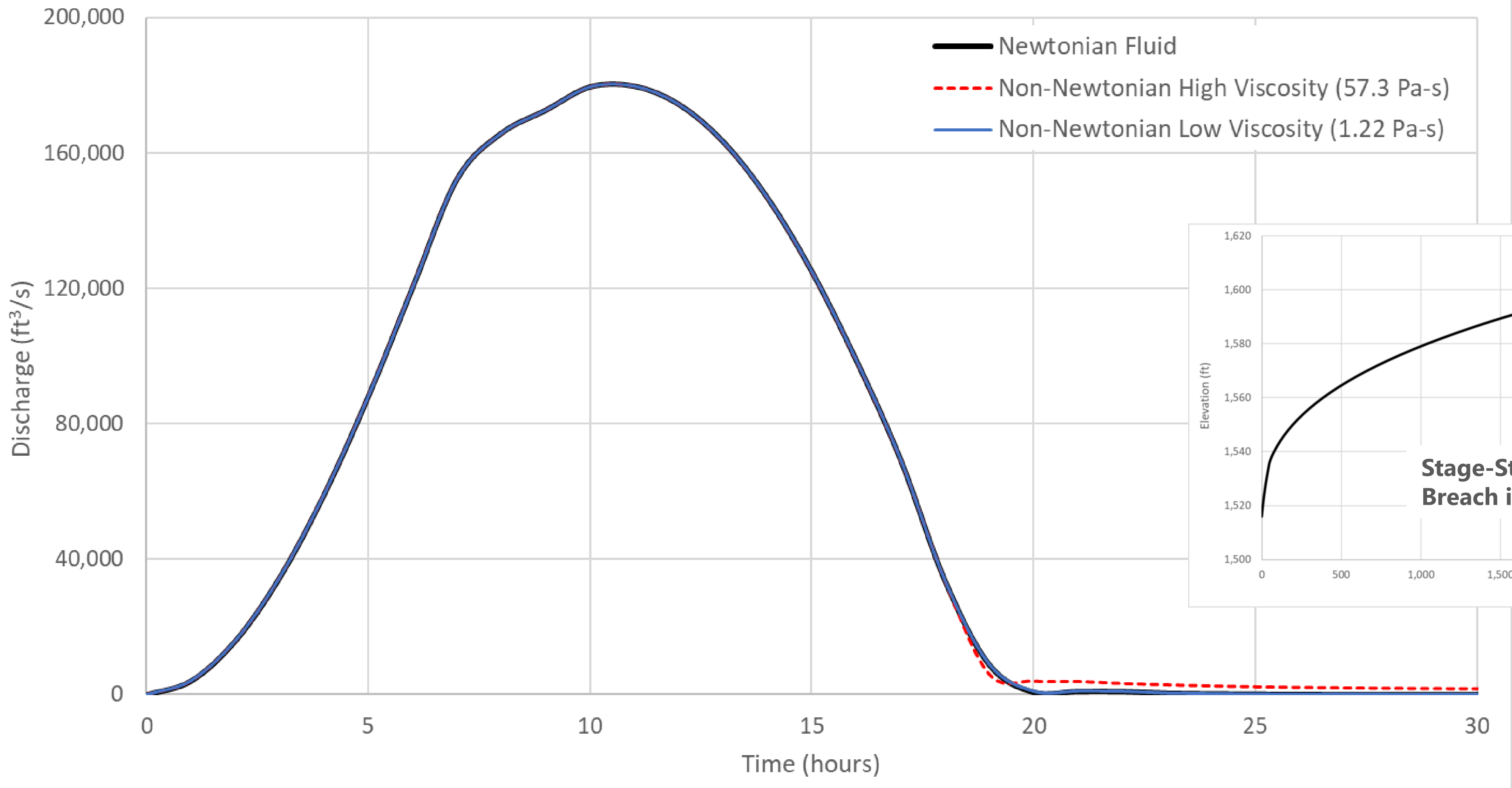
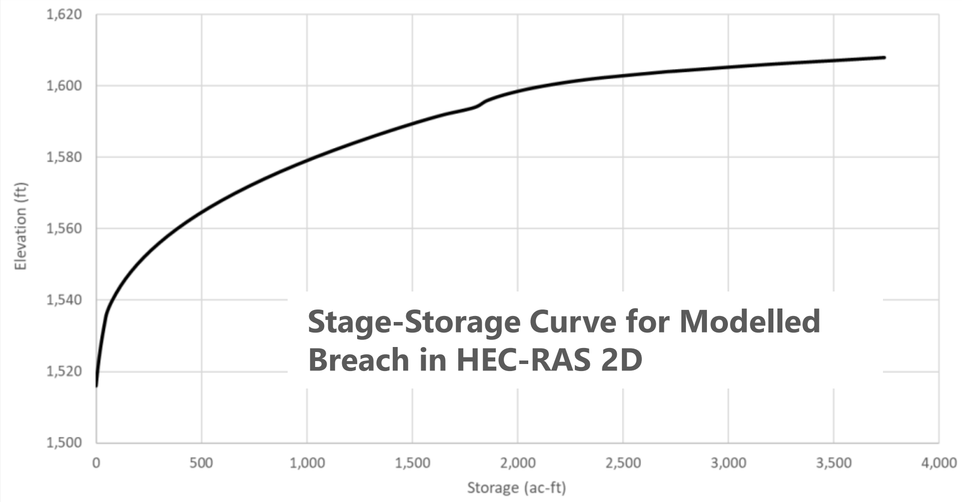
Breach Modelling (Cont'd)

- Comparison 2: HEC-RAS 2D Newtonian vs Non-Newtonian Breach





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Downstream Routing

- Outflow Regime

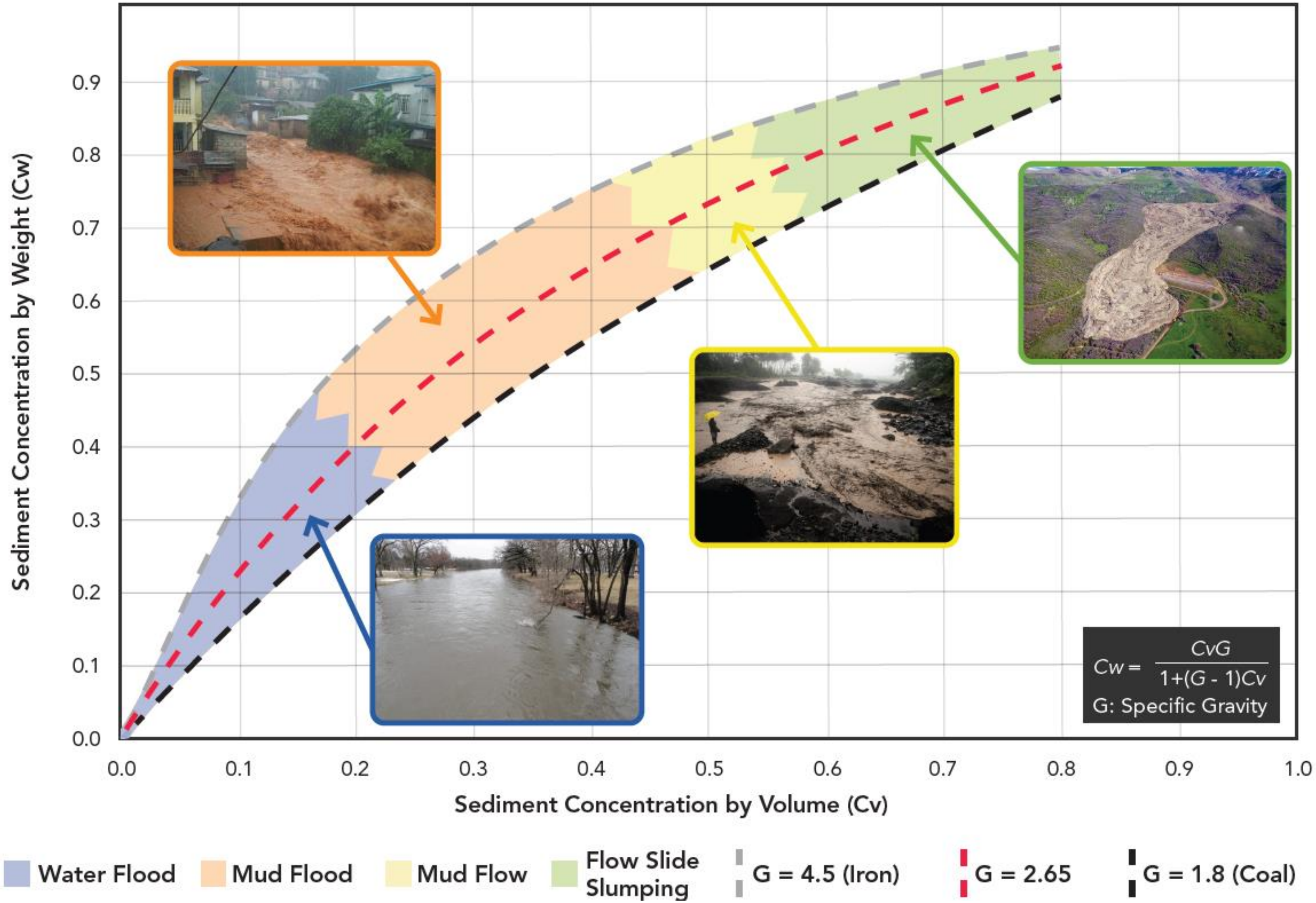

Image Source: CDA

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Downstream Routing (Cont'd)

- Modelling Tools

RAS

FLO-2D

FLOW-3D®

Solving the World's Toughest CFD Problems

DAN-W
Runout Analysis

FLDWAVE

Useful links:

Ghahremani et al. (2022): numerical runout model paper

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

ELSEVIER

Review

A benchmarking study of four numerical runout models for the simulation of tailings flows

Check for updates

Negar Ghahramani [a,*], H. Joanna Chen [b], Daley Clohan [c], Shielan Liu [d], Marcelo Llano-Serna [e], Nahyan M. Rana [f], Scott McDougall [a], Stephen G. Evans [f], W. Andy Take [g]

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Downstream Routing (Cont'd)

- Modelling Tools

Models	Type	Case 1A	Case 1B	Case 2A	Case 2B	Newtonian Fluids	Non-Newtonian Fluids	Computing Cost
DAMBRK	1D	Yes	Yes	-	-	Yes	-	Medium
FLDWAV	1D	Yes	Yes	Yes	-	Yes	Yes	
HEC-RAS	1D/2D	Yes	Yes	Yes	-	Yes	Recently released	
FLO-2D	2D	Yes	Yes	Yes	-	Yes	Yes	
MIKE 11 & MIKE 21	1D/2D	Yes	Yes	Yes	-	Yes	Yes	High
RiverFlow2D	2D	Yes	Yes	Yes	Yes	Yes	Yes	Medium to High
TUFLOW	2D	Yes	Yes	Yes	-	Yes	Recently released	Medium to High
Telemac-MASCARET System	2D/3D	Yes	Yes	Yes	-	Yes	Recently released	Medium to High
FLOW-3D	2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	High
DAN3D	Quasi-3D	-	-	Yes	Yes	-	Yes	Not available commercially
MADFLOW	Quasi-2D/3D	Yes	Yes	Yes	Yes	Yes	Yes	

Image Source: CDA

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Downstream Routing (Cont'd)

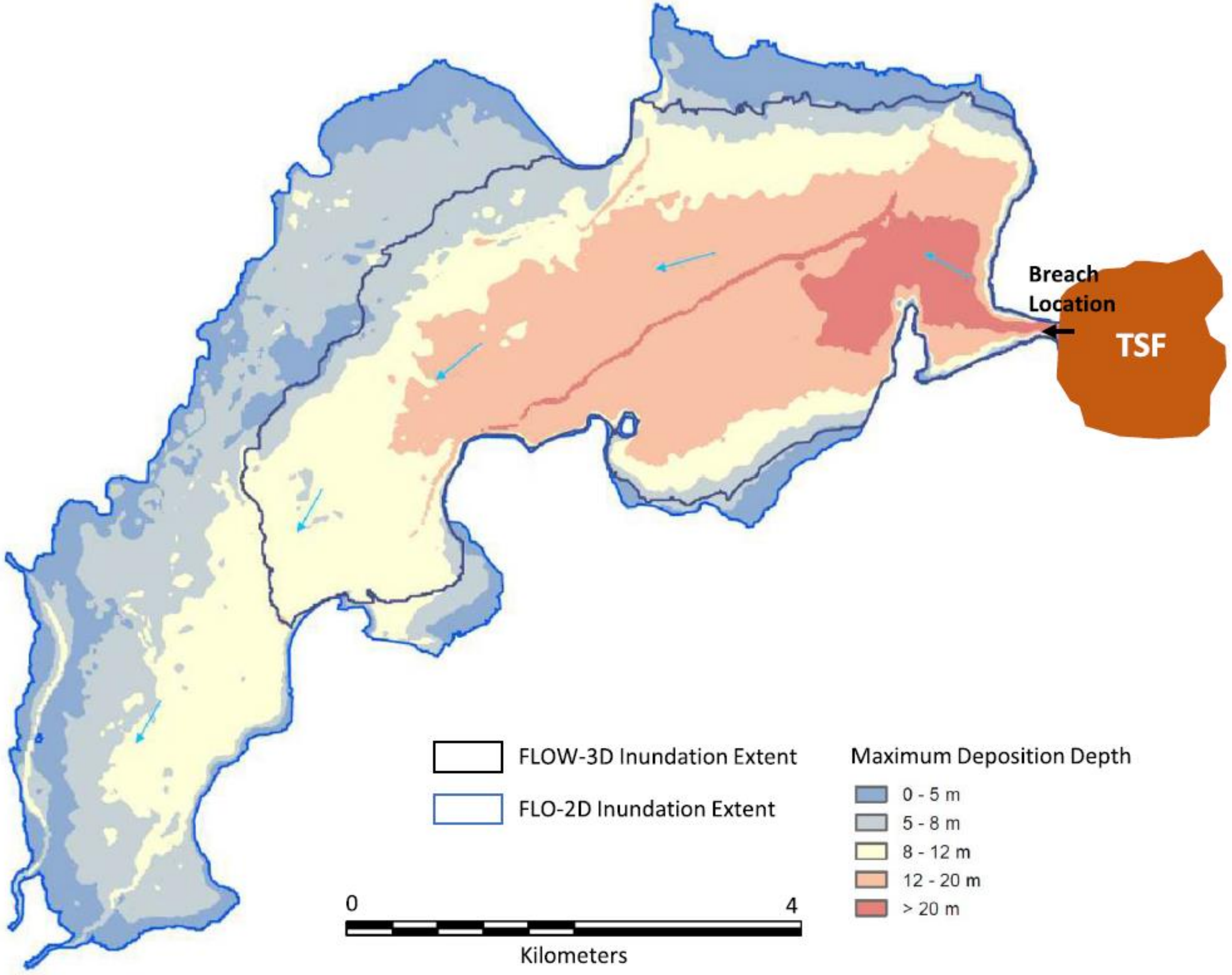

Fig. 10 Comparison of inundation extents between FLO-2D and FLOW-3D

Image Source: Gildeh et al. (2020)

Recommendations and On-going Research

- Some Recommendations…
  - Data & Data & Data & Data.....
  - Multidisciplinary team to tackle TDBA
  - "All models are wrong, but some are useful"
  - Uncertainties! sensitivity analysis on breach parameters (mainly B and t) and tailings rheology (mainly viscosity and yield stress)
  - Stay up-to-date

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Recommendations and On-going Research

- On-going Research
  - CanBreach Project by UBC, Waterloo, Queen's (NSERC and Imperial Oil Resources Inc., Suncor Energy Inc., BGC Engineering Inc., Golder Associates Ltd., and Klohn Crippen Berger)
  - Barr Engineering with University of Ottawa
  - Other universities

Useful links:

CanBreach Project: CanBreach Website

Fig. 12 Downstream oblique view of a typical dam during breach (Source: Walsh et al. 2019)

Image Source: Gildeh et al. (2020)

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Q? & A!

Image Source: scholarlykitchen