Realistic Approach to Tailings Dambreak Analysis Using Site-Specific Parameters and Laboratory Testing

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October 2021

Behnam Pirouz

TAILINGS DAM BREAK ANALYSIS

Toxic leaks from copper-sulphide mine due to dam breach polluting streams in Russia, Photo: Sergey Zamkadniy

Tailings dam break analysis is a numerical modelling process which assists to identify potential impacts (social, economic, environmental) from TSF failure scenarios and the release of tailings/water from the TSF.

It helps to assess the consequence category of the TSF and provides guidance for TSF design and operation.

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OVERVIEW OF THE PRESENTATION

1- Consequence of Tailings Dam Failure

2- Why do we need to simulate Dam Break

3- Different Mechanisms of Failure

4- Simulating Dam Break

- Input Parameters,
- Mathematical model, available simulation tools and limitations

5- What to expect from the simulation, reliability and interpretation of the results

6- Uncertainty in Input Parameters and Sensitivity Analysis

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CONSEQUENCE OF TAILINGS DAM FAILURE

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Brumadino Dam Failure – Brazil (25 January 2019)
Static liquefaction - 270 Deaths

Google Earth image of the site of the Brumadinho tailings dam failure. Image dates 22 July 2018.

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Mariana or Samarco or Fundão Tailings Dam Failure – Brazil (5 November 2015)
Liquefaction of Saturated Sand - 19 Deaths

The Guardian (Photograph: Nicoló Lanfranchi)

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The Mount Polley Tailings Dam Failure – Canada (4 August 2014)
Foundation Failure - 8 million cubic meters of tailings were released

https://www.canadianconsultingengineer.com/

https://www.northernminer.com/

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PHILIP PECK PRESENTATION 2007

UNITED NATIONS

COP to the convention of the transboundary effects of Industrial Accidents

Workshop on the safety of Tailings Management Facilities

November 12, 2007

Yerevan, Armenia

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AVOIDING TAILINGS DAM FAILURES

GOOD PRACTICE IN PREVENTION

Philip Peck

UNEP GRID Arendal and IIIEE at Lund University

TAILINGS SLIME IN RIVERBED DOWNSTREAM OF SASA MINE (MACEDONIA)

Philip Peck Presentation 2007

HEAVY METALS CONTAMINATION OF SOIL AND FOOD (MACEDONIA)

Philip Peck Presentation 2007

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CLEAN-UP OF TAILINGS FROM FARMLAND (MACEDONIA)

Philip Peck Presentation 2007

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Some more brief background

UNITED NATIONS

Why are we here?

Tailings management facilities can and do fail!

This can almost universally be prevented … one key area that helps is

Good Practice in Management & Operations

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WHY DO WE NEED TO SIMULATE DAM BREAK

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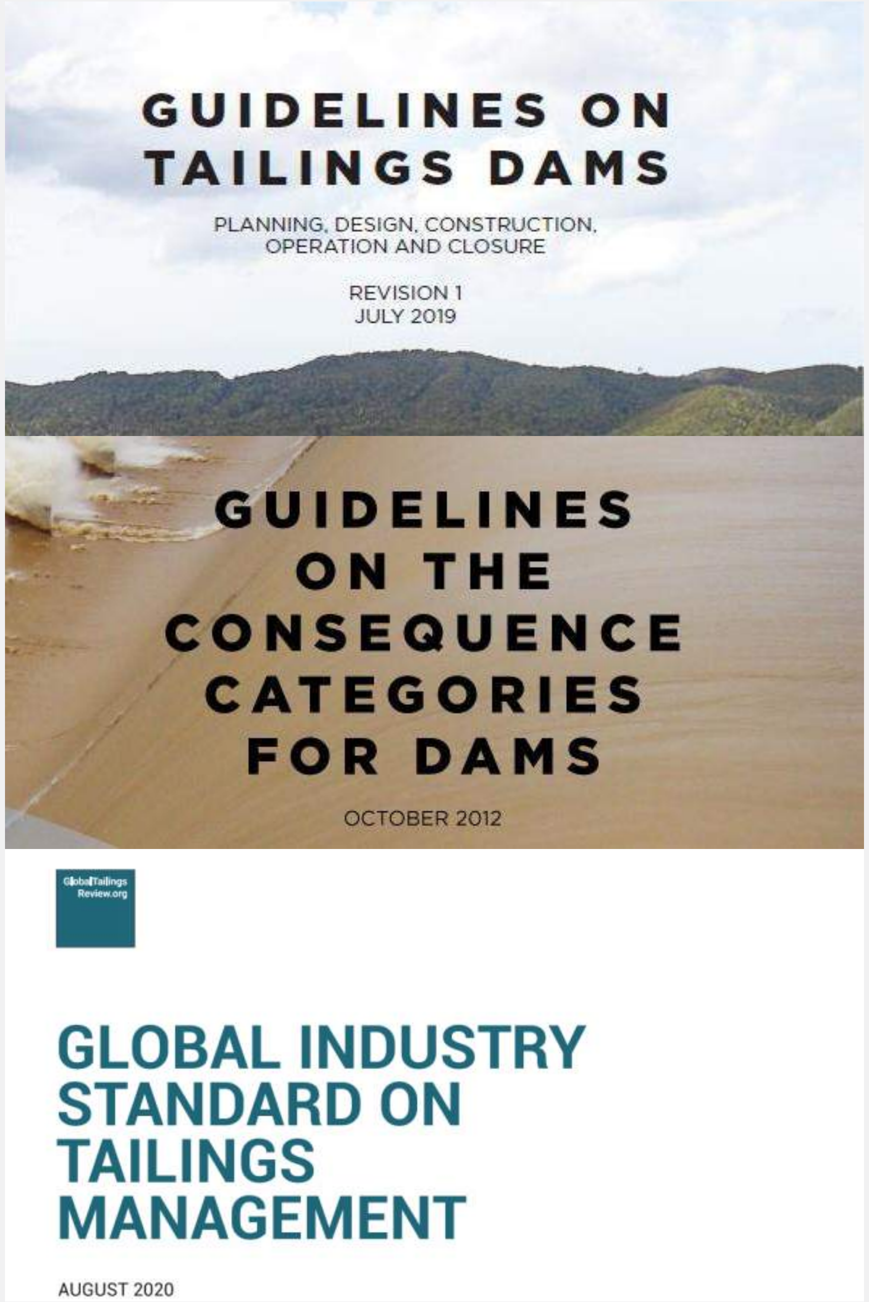
DAM BREAK ANALYSIS – WHY?

- **ANCOLD Guidelines**
  - Inundation Depth and Velocity mapping
  - TSF Consequence Category, Severity of Impact, PAR and PLL to define the design parameters for TSF
  - Emergency Response Plan
- **Global Industry Standard**
  - Credible Failure Scenarios
  - Site-specific Emergency Preparedness and Response Plan



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ANCOLD GUIDELINES ON TAILINGS DAM - 2019

8.6 - Dam Safety Emergency Plan

A Dam Safety Emergency Plan (DSEP), in conjunction with appropriate emergency authority planning, should be prepared for tailings dams where any persons, infrastructure or environmental values could be at risk should the dam collapse or fail.

The DSEP should include an appropriate Dam Break study with the conservative assumption of liquid tailings flow in the event of dam failure unless a more sophisticated analysis of water and/or tailings flow can be justified. DSEP's are to be updated annually and tested at regular intervals.

Dambreak Simulation is undertaken to Save Lives and to Improve Operation to Reduce the Environmental Impact of the TSF

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DIFFERENT MECHANISMS OF FAILURE

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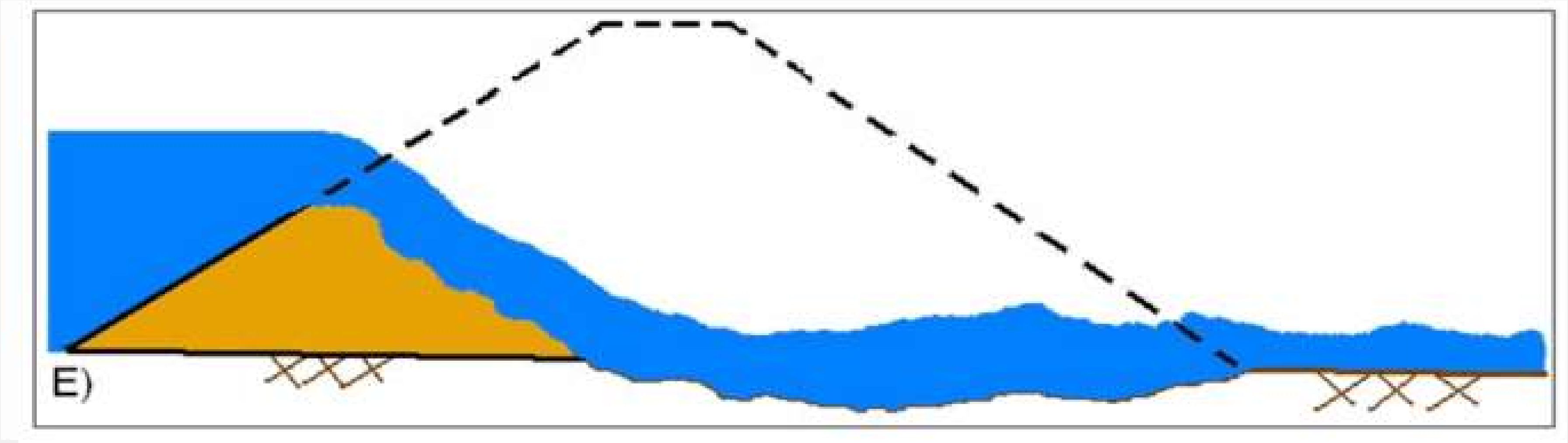
SUNNY DAY FAILURE (SDF) SCENARIO

FAILURE DUE TO A PREVIOUS RAINFALL EVENT OR ACCUMULATION OF PROCESS WATER CAUSING SEEPAGE AND PIPING



(Water Pond at Maximum Operating Level)

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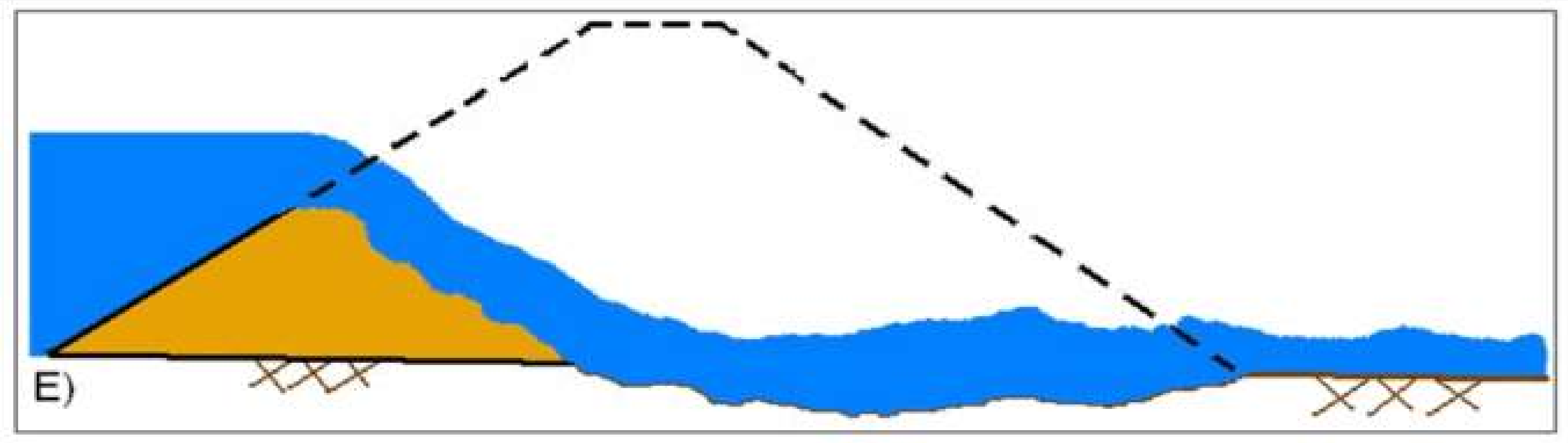
SUNNY DAY FAILURE (SDF) SCENARIO

SUDDEN FAILURE INDUCED BY EARTHQUAKE OR STATIC LIQUEFACTION



(Water Pond at Maximum Operating Level)

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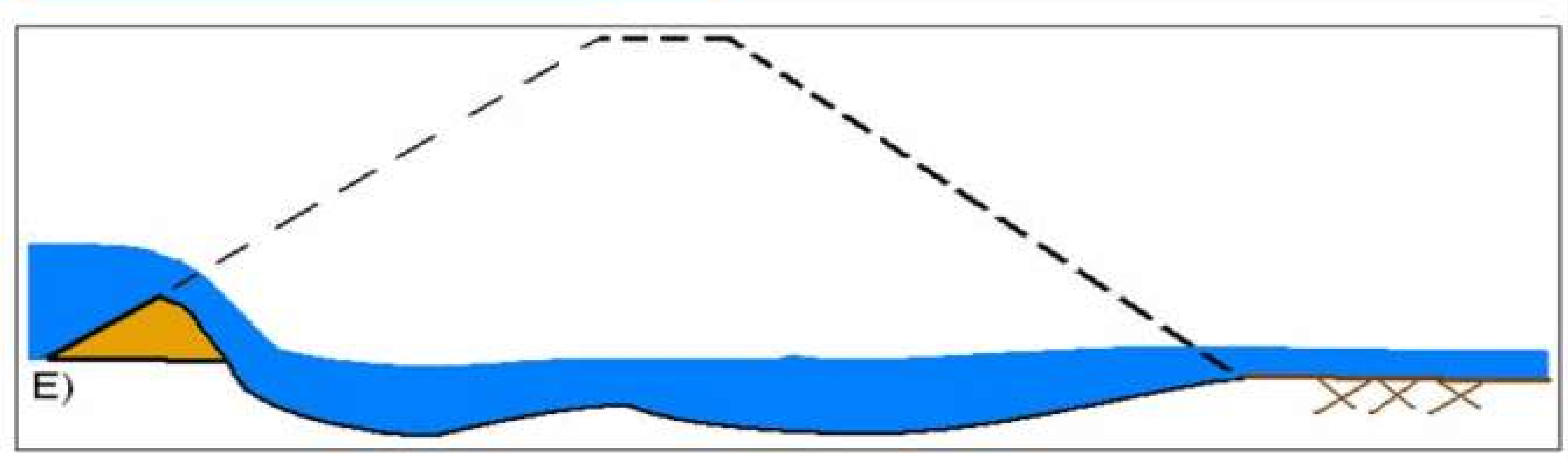
FLOOD FAILURE (FF) SCENARIO

BREACH PROCESS DUE TO OVERTOPPING FAILURE



(Water Pond at Maximum Flood Level)

If the failure of the embankment happens due to overtopping during an extreme flood event, usually it is assumed that the natural catchment downstream of the dam is at peak flow condition prior to failure (i.e. Incremental Impact Assessment)

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RELEASED VOLUME IN RELATION TO DAM HEIGHT AND MECHANISM OF FAILURE (85 DAM)

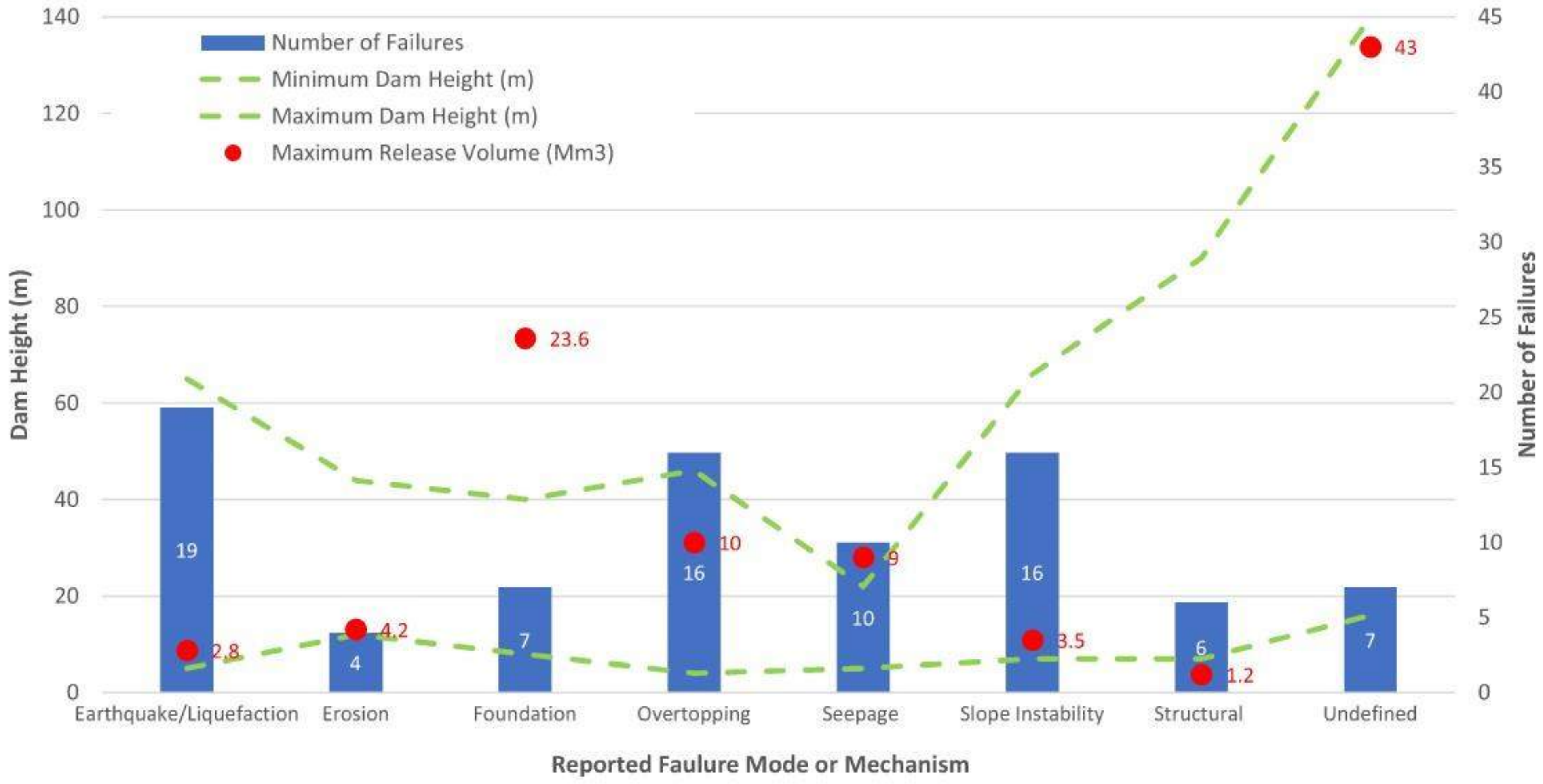

Fig. 2 Release volume in relation to dam height and failure mechanism

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H. Kheikhah Gildeh at.al. 2020 (Mine Water and the Environment)

UPSTREAM DAM FAILURE (46 CASES) DUE TO DIFFERENT FAILURE MECHANISM

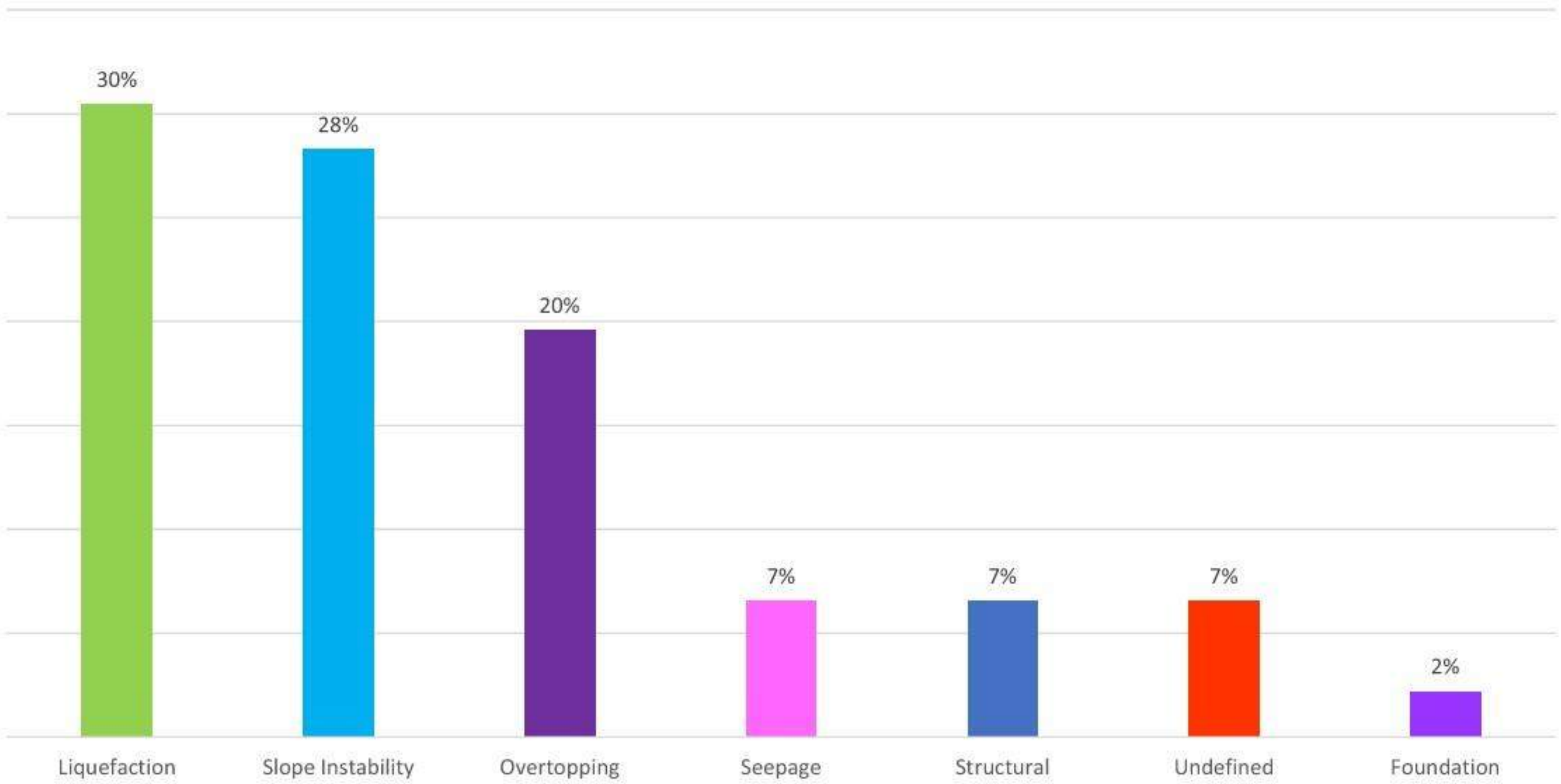

Fig. 3 Upstream dam failure mechanisms

H. Kheikhah Gildeh at.al. 2020 (Mine Water and the Environment)

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SIMULATING DAM BREAK

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STEP 1 – DEFINING CREDIBLE FAILURE MODE

- If SDF with maximum Operating Pond Level is a Credible Scenario?
- If PFF overtopping during the “Design Flood” or “PMP Event” is a Credible Scenario?
- If failure of the dam during flood event while downstream catchment is at peak flow condition is a Credible Scenario?
- If sudden failure of embankment due to Earthquake or Liquefaction is a Credible Scenario?

Avoid creating imaginary scenarios which are near impossible cases and hard to justify (i.e. adding-up multiple rare or extreme events).

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STEP 2 – BASIC INFORMATION AND STUDIES

- Defining the study area, modeling domain, area of interest and model boundaries
- Reliable topography info and generating 3D DEM for the study area
- Catchment and Downstream Hydrology and Flood Study
- Operation Details (water pond level, volume and location)

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STEP 3 – SITE INVESTIGATION AND COLLECTING SITE DATA

- Density Profile with Depth for the Deposited Tailings
- Are the deposited tailings Saturated? Is there is any possibility that they may get Saturated in the future? Phreatic Surface within the tailings deposit.
- CPT, Shear Vane Data
- Liquefaction Study and Assessment (Are the tailings or embankment foundation material are liquifiable?)
- Defining Shear Strength Ration (Post-Liquefied Shear Strength Ratio)

$$K = \frac{S_u}{\sigma'_{V0}}$$

(Olson, S.M. and Stark, T.D., 2002. Liquefied strength ratio from liquefaction flow failure case histories. Canadian Geotechnical Journal, 39(3), pp.629-647.)

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STEP 4 – LABORATORY TESTING

- Basic Testing (PSD, SG, LL)
- Rowe Cell Test (Estimation of Density Profile with depth in Deep Deposits)
- Shrinkage Limit Density Test (Strength gain with Density)
- Cyclic Triaxial, Cyclic Simple Shear (Liquefaction Analysis and Residual Strength)
- Rheology Testing (Bob & Cup and Shear Vane) to estimate flow properties: (Herschel–Bulkley Model or Bingham Plastic Model Parameters)

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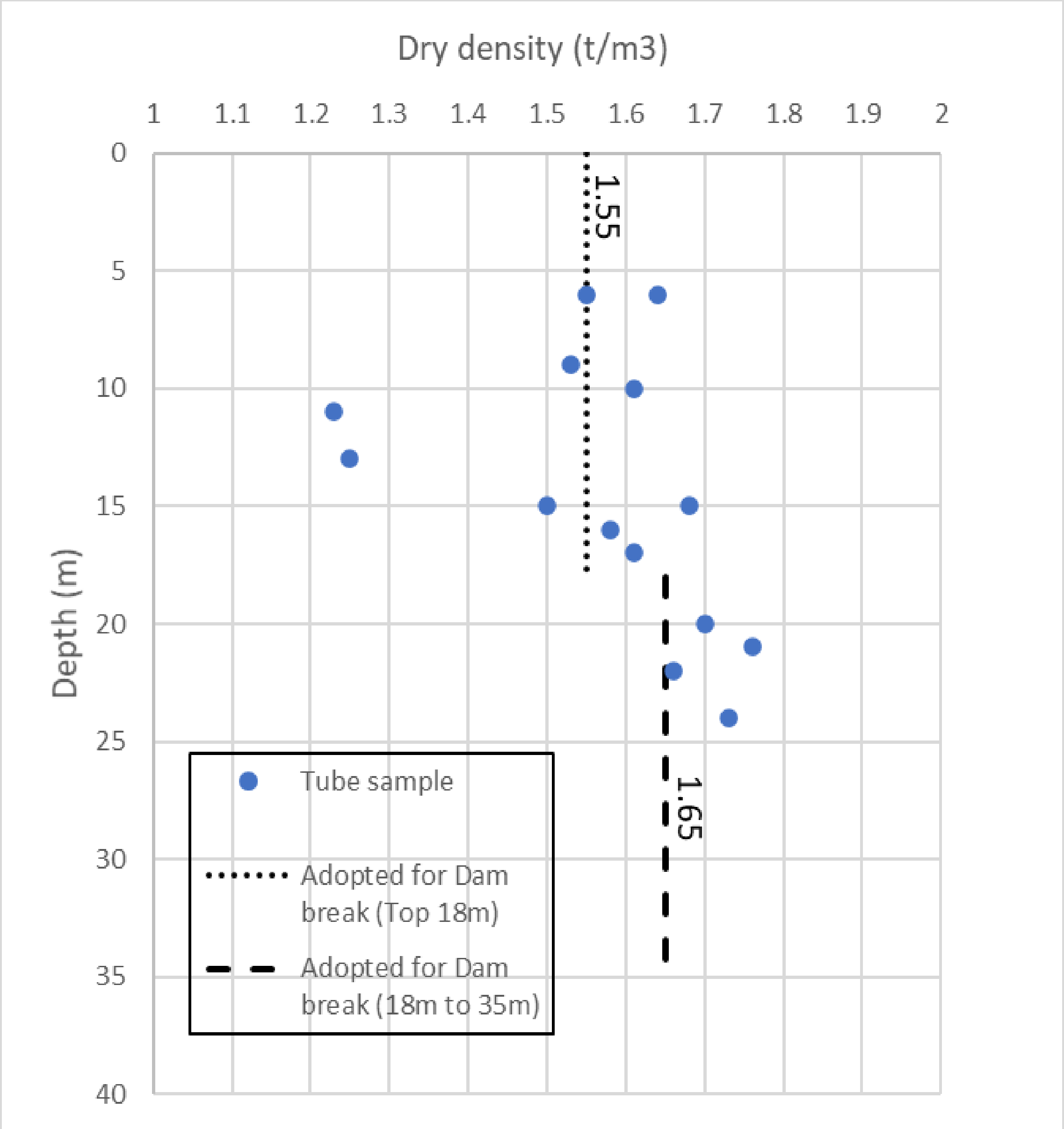
DENSITY PROFILE WITH DEPTH



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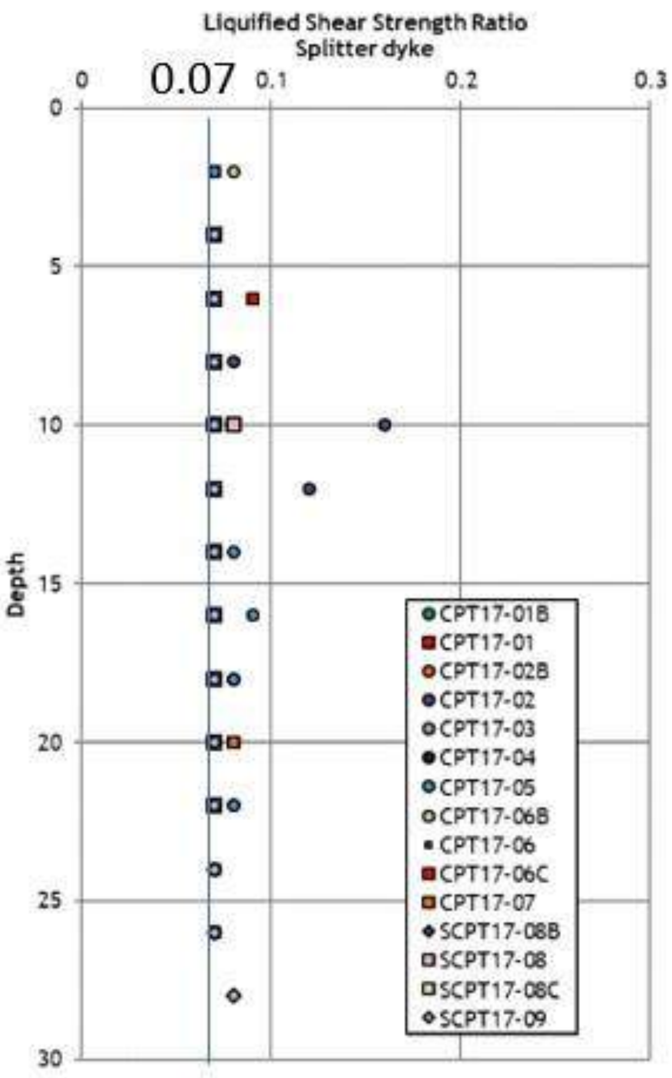
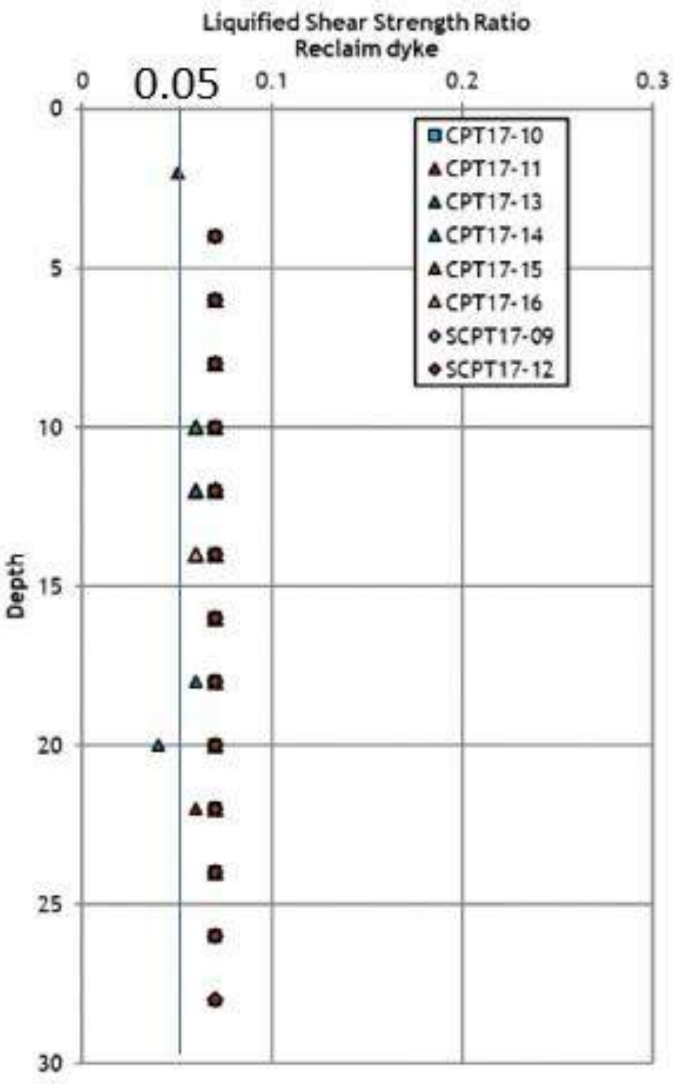
CPT TEST RESULTS – LIQUEFIED STRENGTH RATIO





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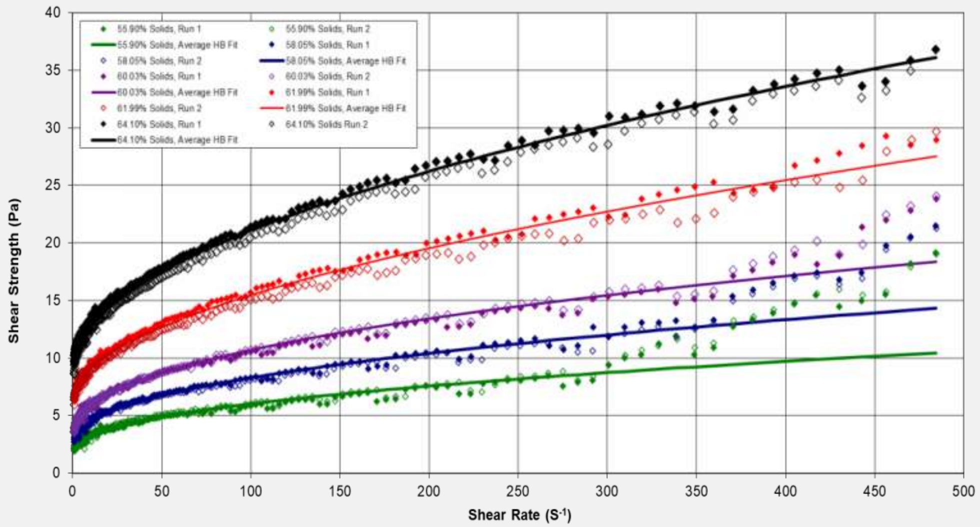
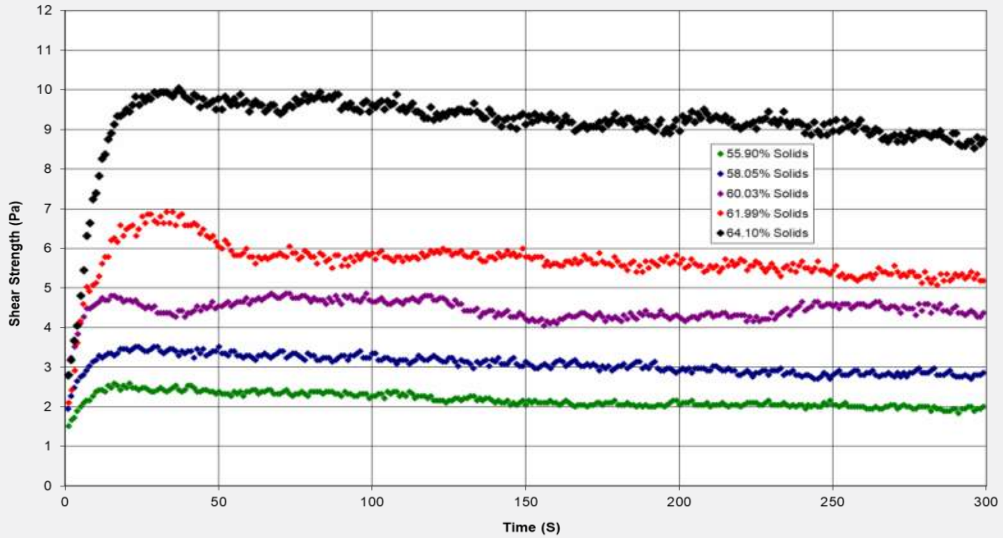
RHEOLOGY TESTING RESULTS





Herschel-Bulkley Model describes the flow behaviour of yield-pseudo-plastic fluids with the following equation:

$$\tau = \tau_y + K\dot{\gamma}^n \qquad \text{(Equation 1)}$$

Where

τ = shear stress;

τ_y = yield stress;

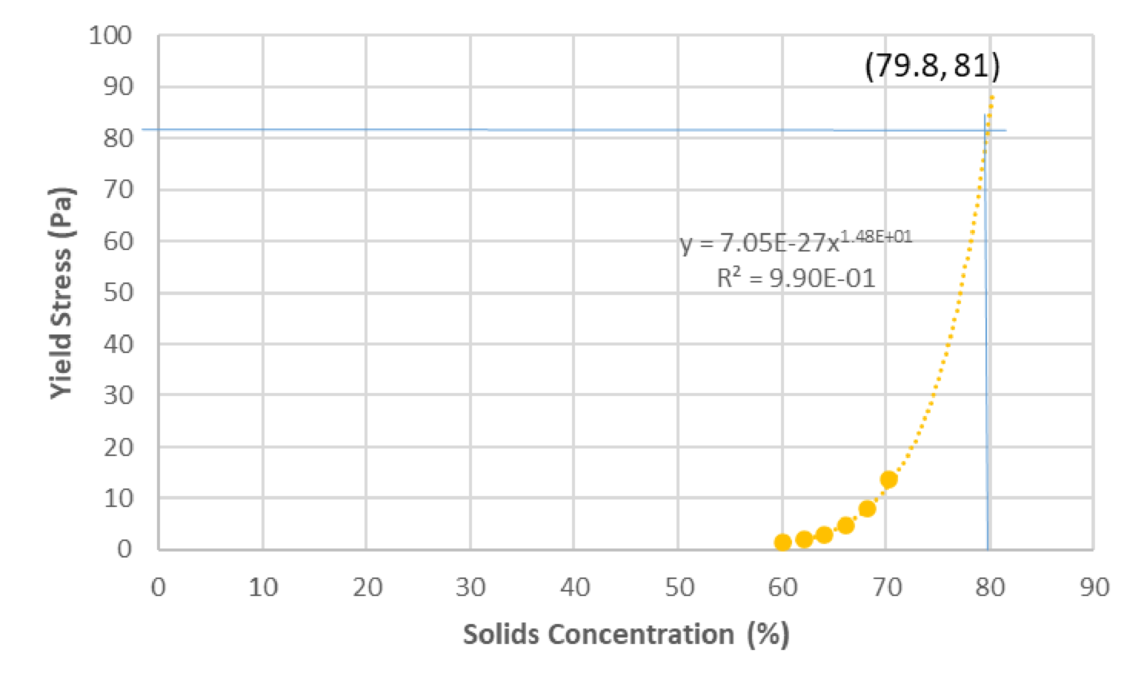
K and n = fluid parameters and

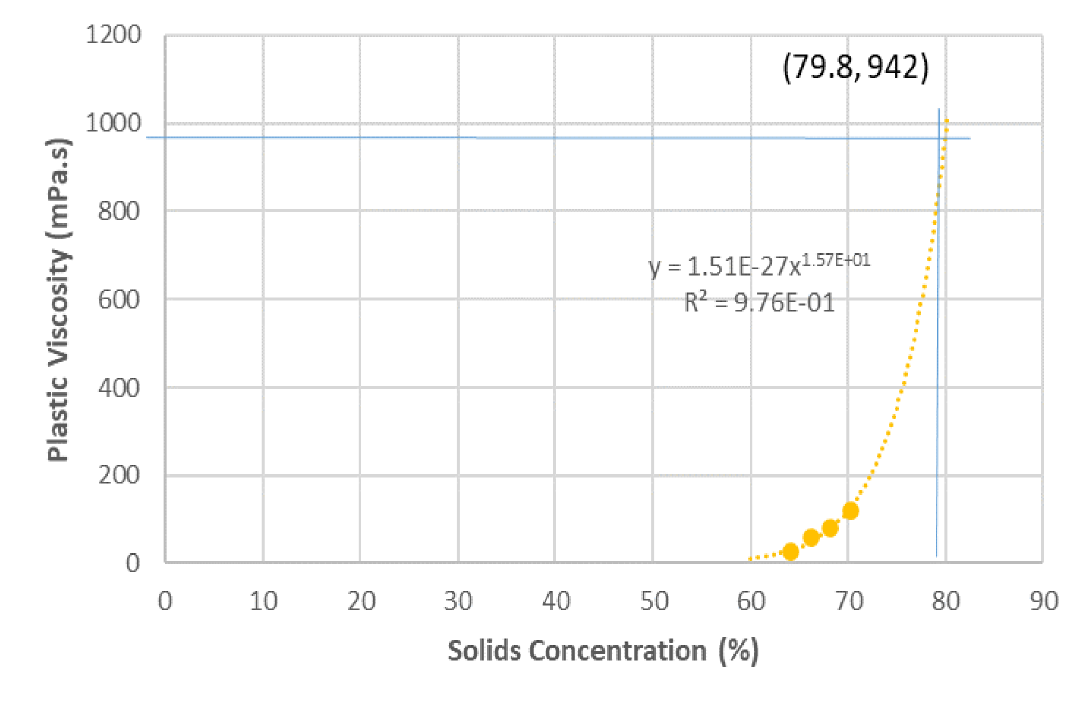
$\dot{\gamma}$ = shear rate

For n=1, the Herschel Bulkely Model converts to Bingham Plastic Model which is used to describe the viscoplastic material with the following equation:

$$\tau = \tau_y + K\dot{\gamma} \qquad \text{(Equation 2)}$$

YIELD STRESS AND VISCOSITY VS SOLIDS CONCENTRATION





Yield Stress and Viscosity are defined in terms of Slurry Solids Concentrations

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STEP 5 - FAILURE SLOPE AND RELEASED VOLUME

The equations derived from the stability of long, shallow slopes (i.e. Infinite Slope Theory). The theory assumes that after liquefaction of the tailings, the tailings strength would be greatly reduced, resulting in the slumping of the tailings until the tailings reach a slope where force balance has been achieved. The equation is given by:

$$S_u = \gamma h \sin\beta \cos\beta$$

where

S_u = *undrained, post-liquefaction shear strength,* $S_{u,res}$

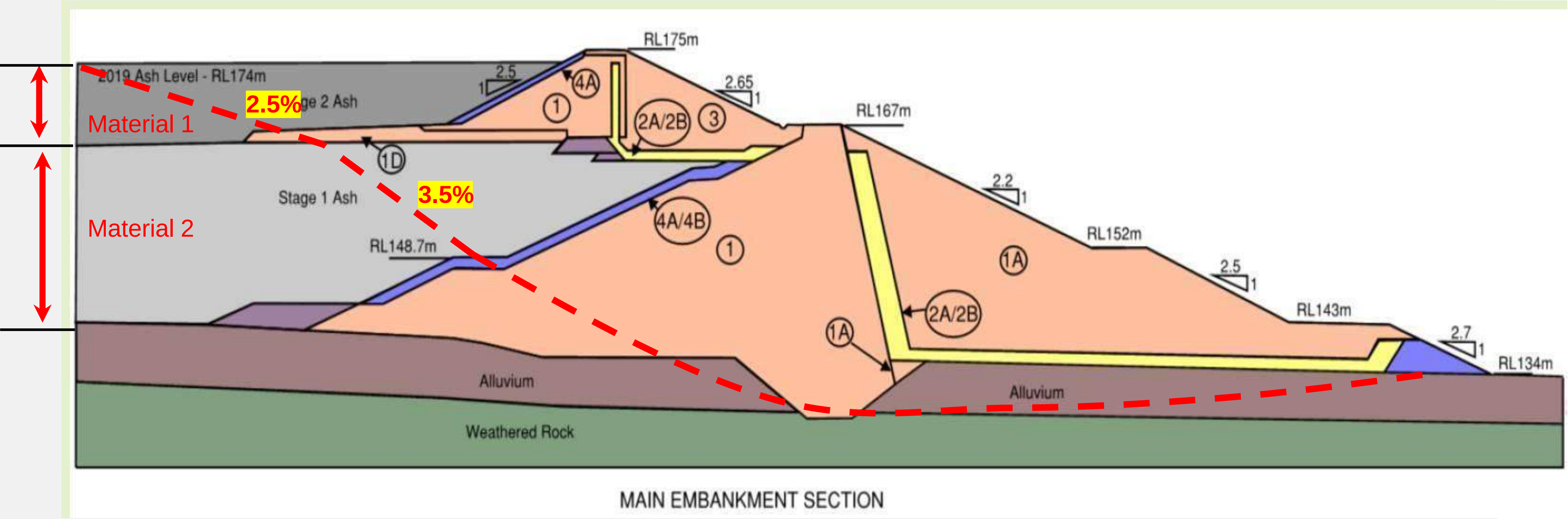
γ = *total unit weight of* Tailings

h = *depth of ash*

β = *failure slope angle*

Seddon, K.D. (2007), "Post-Liquefaction of Thickened Tailings Beaches", Proceedings of the 10th International Seminar on Paste and Thickened Tailings (Paste 2007), Perth, Australia, pp. 395-411.

SITE INVESTIGATION AND COLLECTING SITE DATA



Material 1: In-situ Dry Density 1.55 t/m3, Post-Liquefied Shear Strength Ratio =0.05, **Slope =2.5%**

Material 2: In-situ Dry Density 1.65 t/m3, Post-Liquefied Shear Strength Ratio =0.07, **Slope =3.5%**

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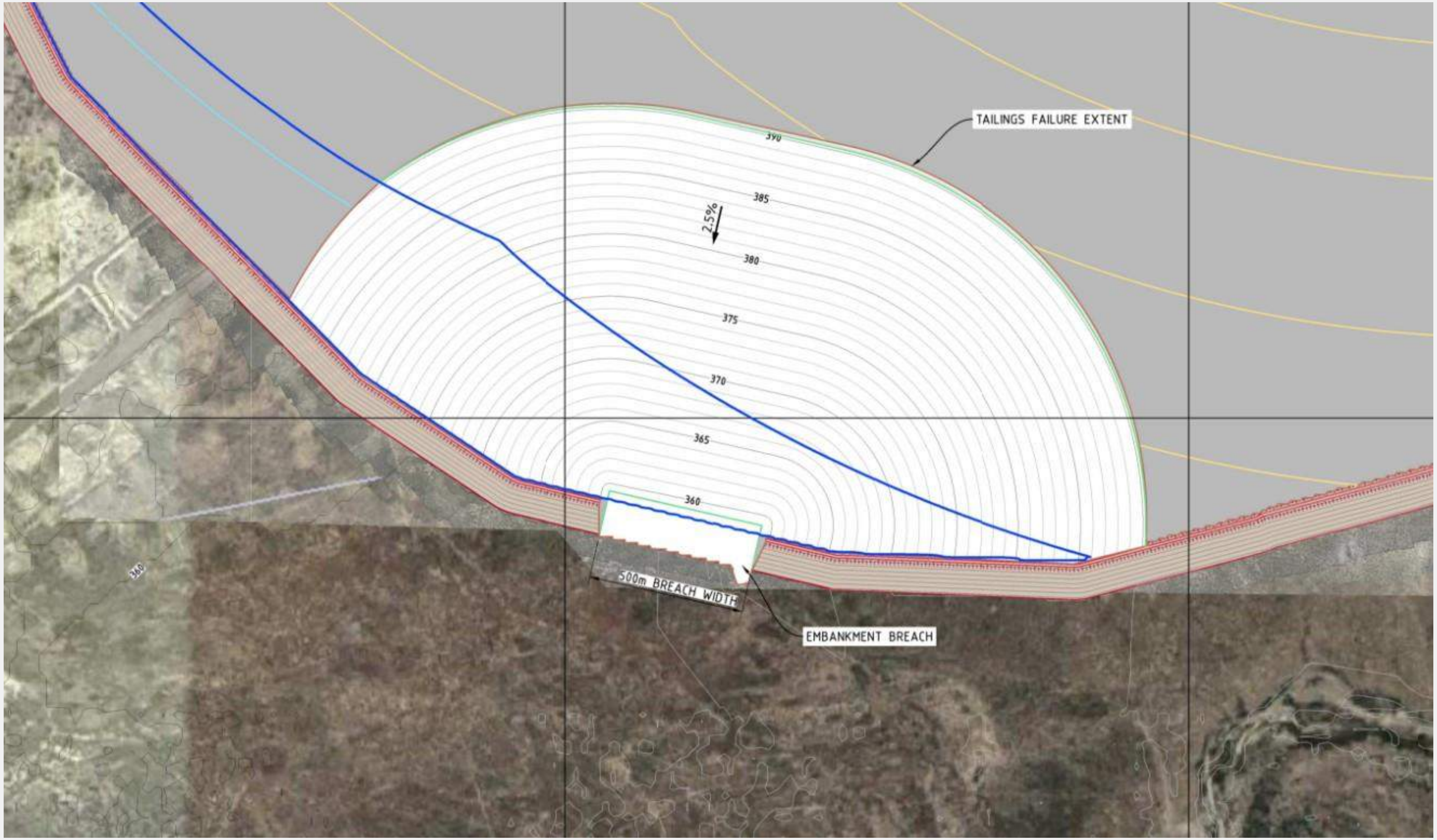
FAILURE SURFACE AND RELEASED VOLUME



Saturated and Liquefied Tailings

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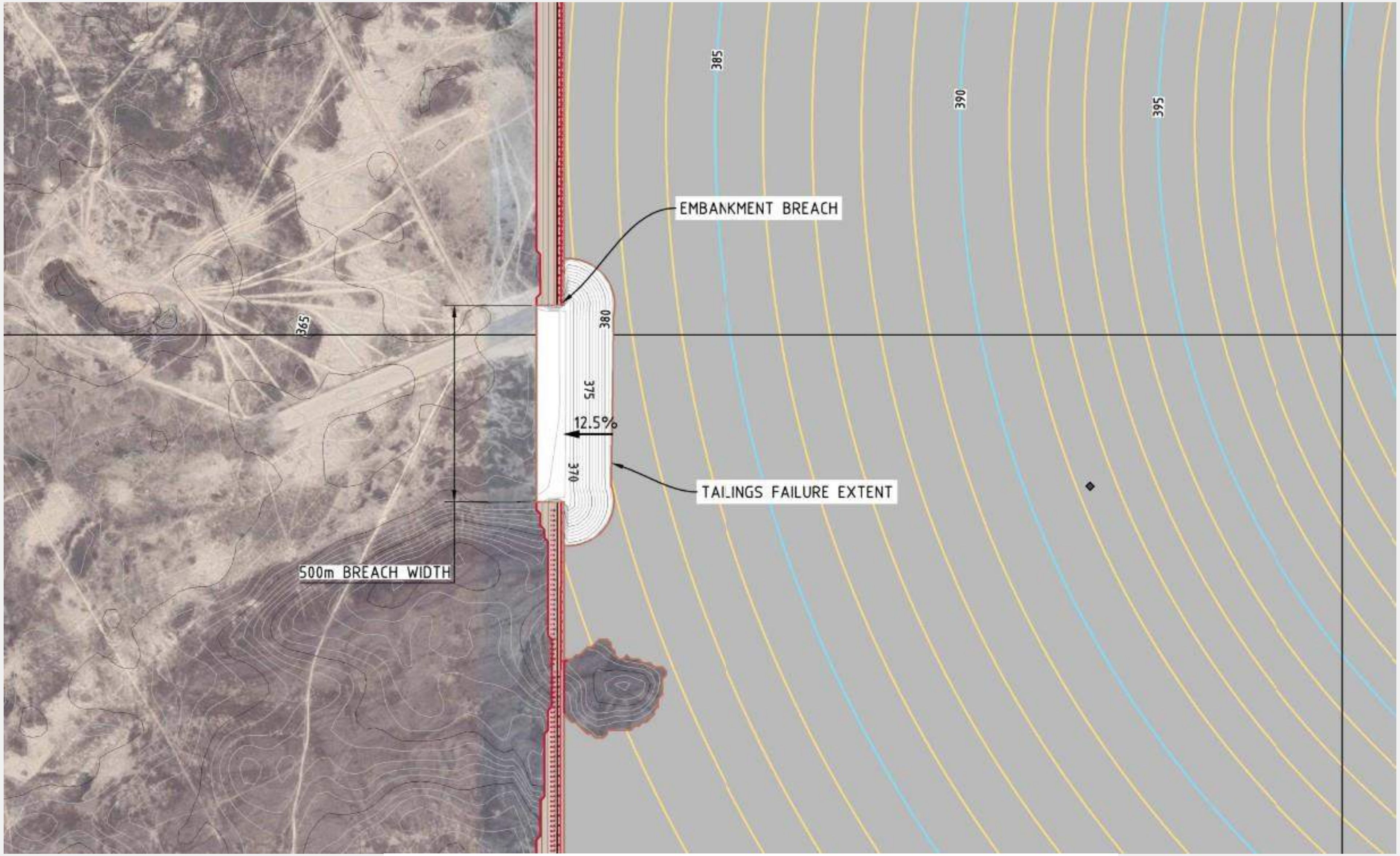
FAILURE SURFACE AND RELEASED VOLUME



Un-Saturated and Un-Liquefied Tailings

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BREACH PARAMETERS
(OVERTOPPING AND PIPING FAILURE)

The following regression equations have been used for several dam safety studies found in the literature (except the Xu and Zhang equations, which are presented because of their wide range of historical data values), and are presented in greater detail in this document:

- Froehlich (1995a)
- Froehlich (2008)
- MacDonald and Langridge-Monopolis (1984)
- Von Thun and Gillette (1990)
- Xu and Zhang (2009)

ANCOLD 2014 (Paper)
Review of Embankment Dam Breach Parameter Prediction Methodologies
Sam J. F. Knight
David C. Froehlich

Database of 88 Dam Failure is used to assess the accuracy of four methods. The Froehlich (2008) method provided the best fit.

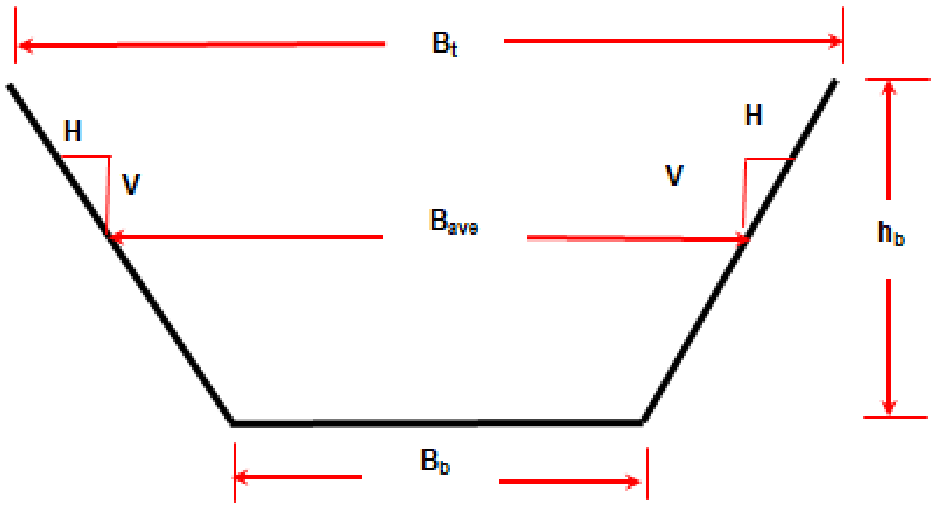
BREACH PARAMETERS (OVERTOPPING AND PIPING FAILURE)

Estimation of Breach Parameters from an Overtopping after an Earthquake - Froehlich (2008) Method

Inputs:
Embankment Crest RL =70m
Tailings Surface Max RL = 68m
Railings Surface Min RL = 66.5m
Embankment Base RL = 53m
Total Embankment Height = 17m
Total Tailings Depth = 15m
Total Storgae Volume = 1.3 Mm^3

Geometry of the breach at Start:
Breach Invert Level = 66.5m
B_b = 1m
B_t = 2.7m
B_{ave} = 1.8m
Side Slope = 1H:1V

Geometry of the Breach at Completion :
Breach Invert Level = 53m
B_b = 20m
B_t = 50m
B_{ave} = 35m
h_b = 15m
Side Slope = 1H:1V
t_f (Breach formation Time) = 0.42hr



Froehlich's regression equations for average breach width and failure time are:

$$B_{ave} = 0.1803\, K_o\, V_w^{0.32}\, h_b^{0.19}$$

$$t_f = 0.00254\, V_w^{0.53}\, h_b^{-0.90}$$

where:
B_{ave} = average breach width (meters)
K_o = constant (1.4 for overtopping failures, 1.0 for piping)
V_w = reservoir volume at time of failure (cubic meters)
h_b = height of the final breach (meters)
t_f = breach formation time (hours)

Froehlich states that the average side slopes should be:

1.4H:1V overtopping failures
0.9H:1V otherwise (i.e., piping/seepage)

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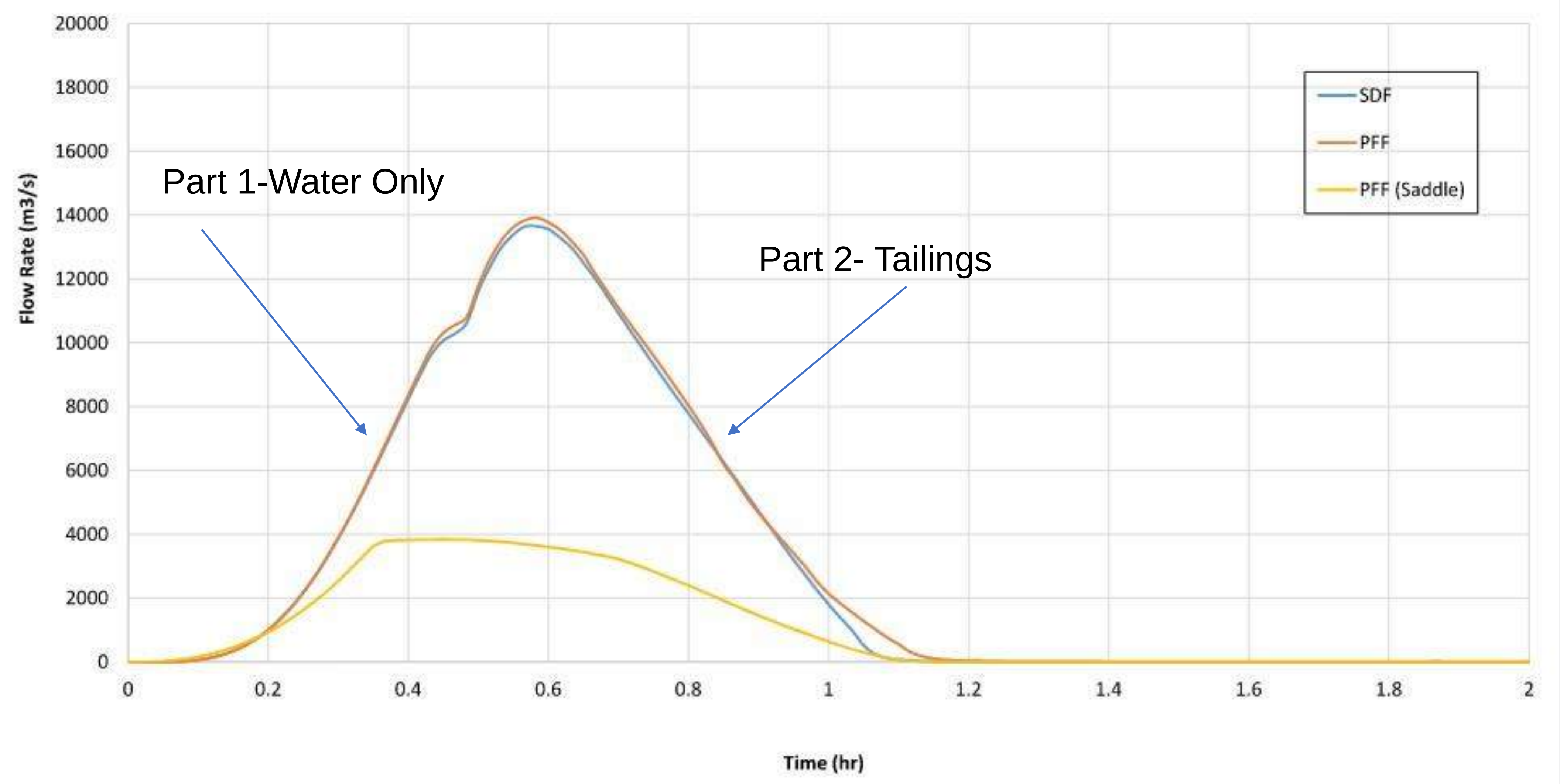
STEP 6 - RELEASED OUTFLOW HYDROGRAPH SHAPE



STEP 7 – SIMULATION OF FAILURE SCENARIO

- Selecting a Modeling Tool with Non-Newtonian Flow Analysis Capability and Consideration of Solids Particles

- **Note:** Assuming water like properties for tailings Dambreak Analysis is not necessarily conservative assumption.

- Always check the fundamental <u>mathematical model built-in the software package</u> and make sure that it includes the <u>Turbulent Terms in the Energy Loss Equation</u>!

Several Modelling Tools are available:

- Flo2D
- River Flow 2D
- Flow 3D
- DAN-W

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STEP 7 – SIMULATION OF FAILURE SCENARIO

Notes:

- None of commercially available modelling software package are developed for Slurry (Tailings) Flow!
- Most of them are for Simulation of Natural River Mudflows
- No analytical or true semi-imperial solution exist for Turbulent flow of slurry in Open Channels, but some of the existing models can be modified to provide a reasonable approximation for Dam Break simulation

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STEP 7 – SIMULATION OF FAILURE SCENARIO

The friction slope components can then be combined in the following form:

$$S_f = \frac{\tau_y}{\gamma_m h} + \frac{K \eta V}{8 \gamma_m h^2} + \frac{n_{td}^2 V^2}{h^{4/3}}$$

Yield Stress Term | Viscosity Term | Turbulent Term

FLO-2D

This is a very rough and crude estimation of the Head Loss in Non-Newtonian Fluid Flow, but reasonably acceptable for Dambreak Analysis

STEP 7 – SIMULATION OF FAILURE SCENARIO

Notes:

- Using simulation Tools or Software that only have "Laminar Regime Equations" as their built-in model will cause Over-prediction of the Flow Velocity and Under-prediction of the Flow Depth

- As long as the Fundamental Equation for Turbulent Flow of Non-Newtonian Fluid in Open Channel (carrying solids particles) is not improved, using more sophisticated numerical modeling techniques (such as CFD) for Dambreak analysis would not increase the accuracy of the analysis and results!

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Brumadinho Tailings Dam Failure

Tailings Discharge From Spigot

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STEP 7 – SIMULATION OF FAILURE SCENARIO

ATCW Open Channel Flow Model for Thickened Slurry

Javadi, S. (2017). Laminar, transitional and turbulent flow of thickened tailings in open channels [RMIT University].

Non-Newtonain Open Channel Flow Modelling (Javadi, S. (2017))

Fully Turbulent

$$\frac{V}{u^*} = \frac{1}{k} ln(\frac{\rho u^* R_h}{11.38\alpha\mu}) + \frac{\beta}{k}((1 - \frac{11.38\alpha\mu}{\rho u^* R_h}) \times \ln\left(1 - \frac{11.38\alpha\mu}{\rho u^* R_h}\right) - \left(1 - \frac{11.38\alpha\mu}{\rho u^* R_h}\right)$$

Where	V	: Average Velocity (m/s)
	u_*	: Shear velocity (m/s)
	ρ	: Slurry Density (kg/m^3)
	R_h	: Hydraulic Radius (m)
	μ	: Plastic viscosity (Pa.s)
	k	: Von Karman Constant

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STEP 7 – SIMULATION OF FAILURE SCENARIO

ATCW Open Channel Flow Model for Thickened Slurry

Javadi, S. (2017). Laminar, transitional and turbulent flow of thickened tailings in open channels [RMIT University].

Transitional Regime

$$\frac{V}{u^*} = \frac{1}{k} ln(\frac{\rho u^* R_h}{11.38\alpha\mu}) + \frac{\beta}{k}((1 - \frac{11.38\alpha\mu}{\rho u^* R_h}) \times \ln\left(1 - \frac{11.38\alpha\mu}{\rho u^* R_h}\right) - \left(1 - \frac{11.38\alpha\mu}{\rho u^* R_h}\right) - \theta$$

$$\theta = \frac{1}{k}(\frac{ln\frac{\tau_w}{\tau_y}}{1 - \frac{\tau_y}{\tau_w}}) + \frac{1}{k} exp(\frac{-b}{2R_h})$$

Applying the model for Dambreak Simulation is currently Work in Progress!

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WHAT TO EXPECT FROM THE SIMULATION, RELIABILITY AND INTERPRETATION OF THE RESULTS

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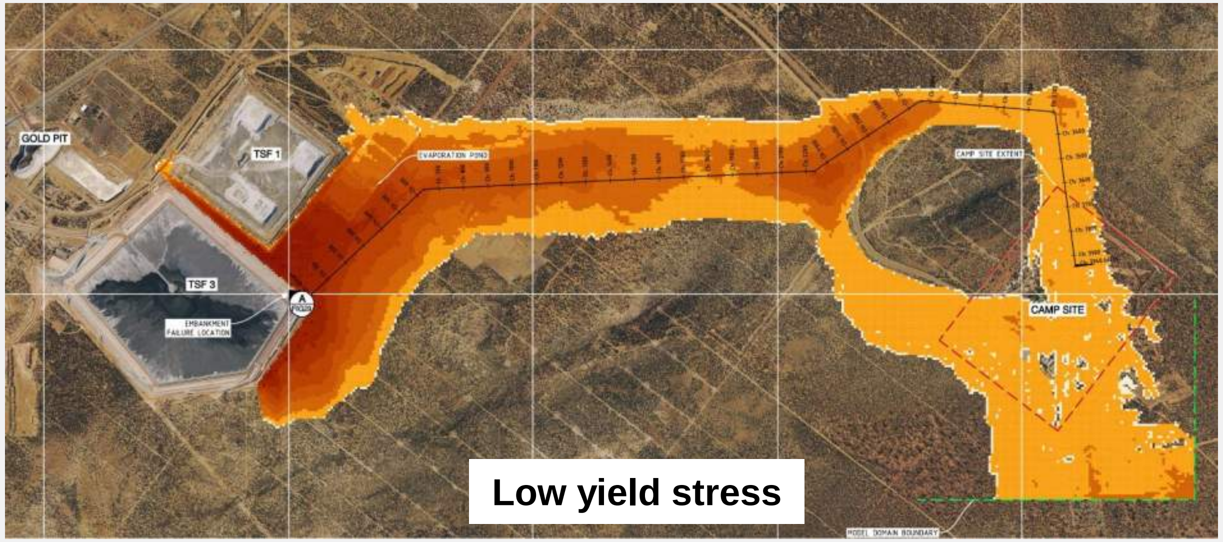
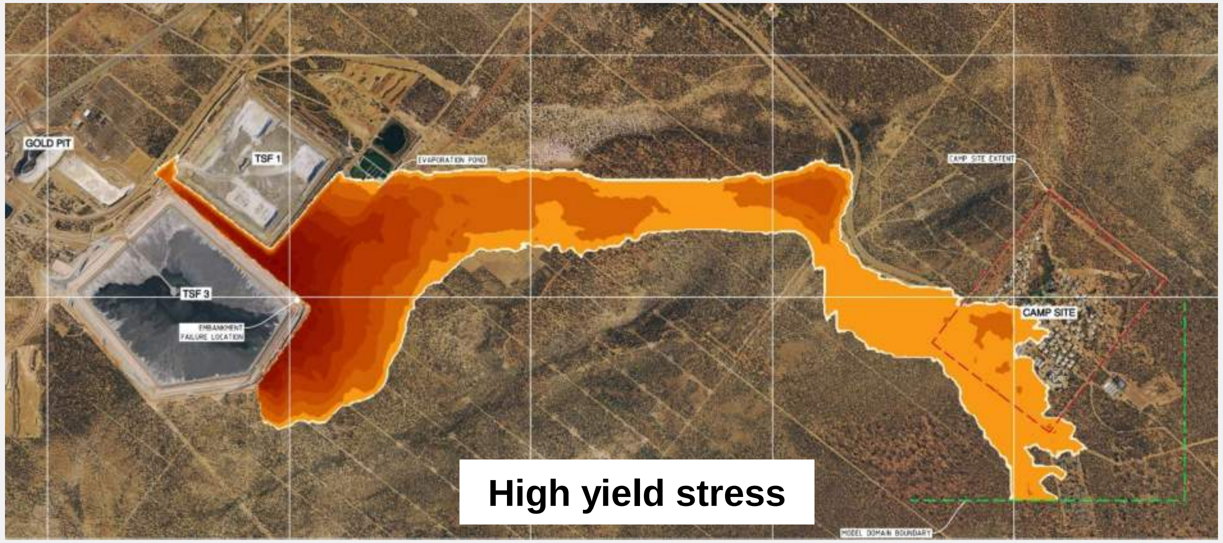
APPLICATIONS NON-NEWTONIAN FLOW ANALYSIS

Using Non-Newtonian flow model results in:

- More realistic outcomes comparing to water like flow simulation
- Defining “Flow Depth” and “Flow Velocity” relationship
- Flow cessation due to Yield Stress Properties
- Sensitivity of the analysis and results to Tailings Properties: Density and Rheology (yield stress)





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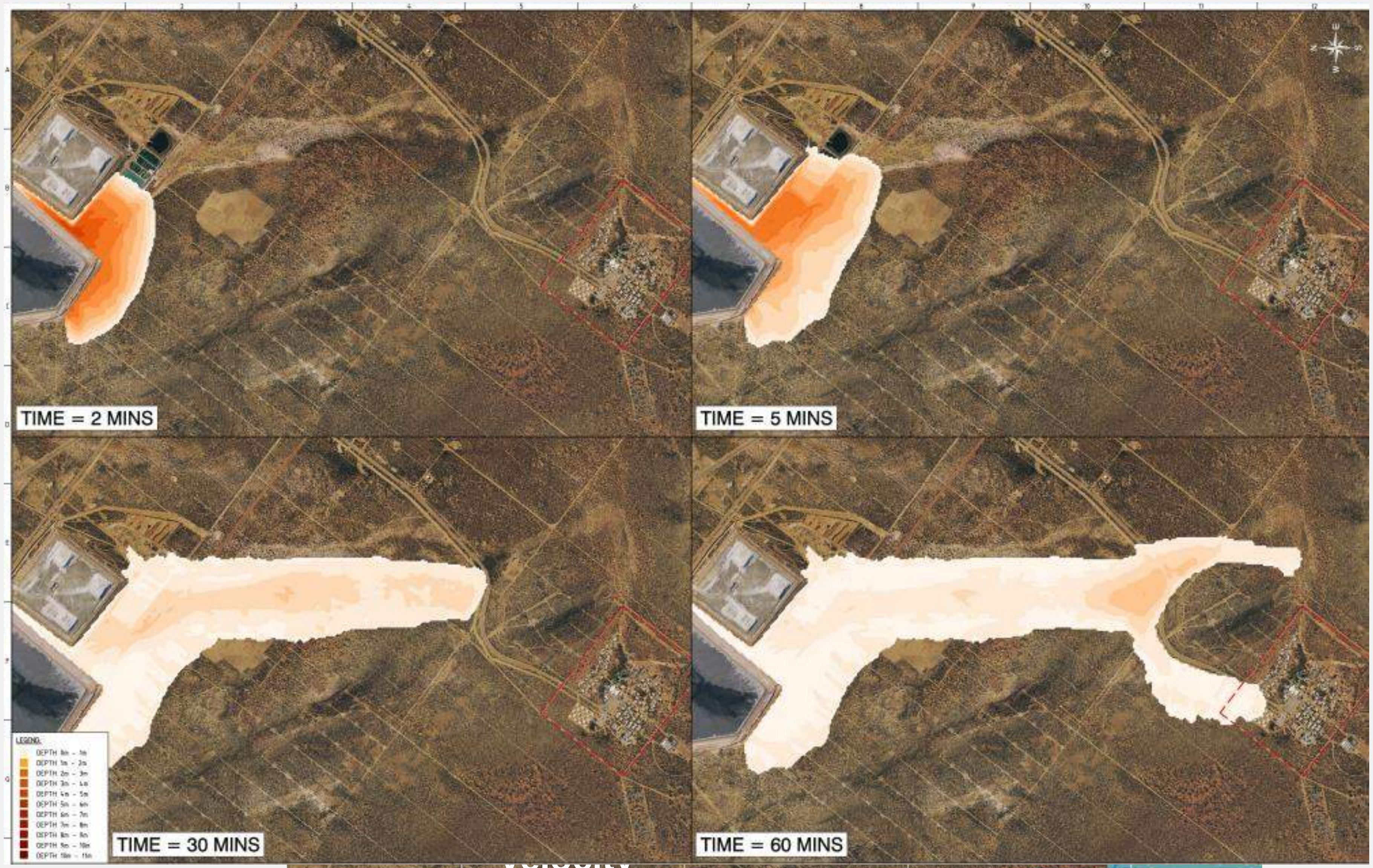
CASE STUDY 1



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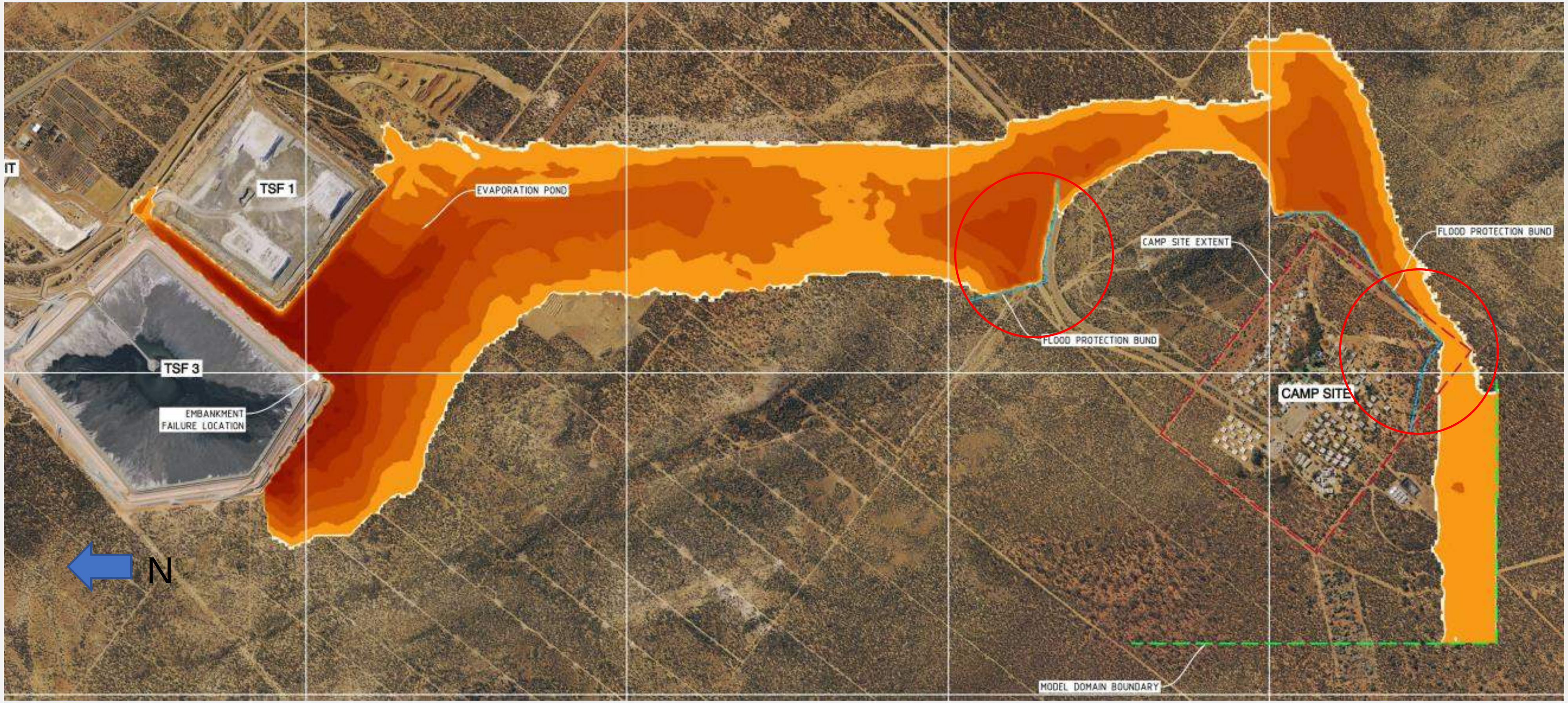
CASE STUDY 1

Designing Protection Dyke to Reduce PAR



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CASE STUDY 2

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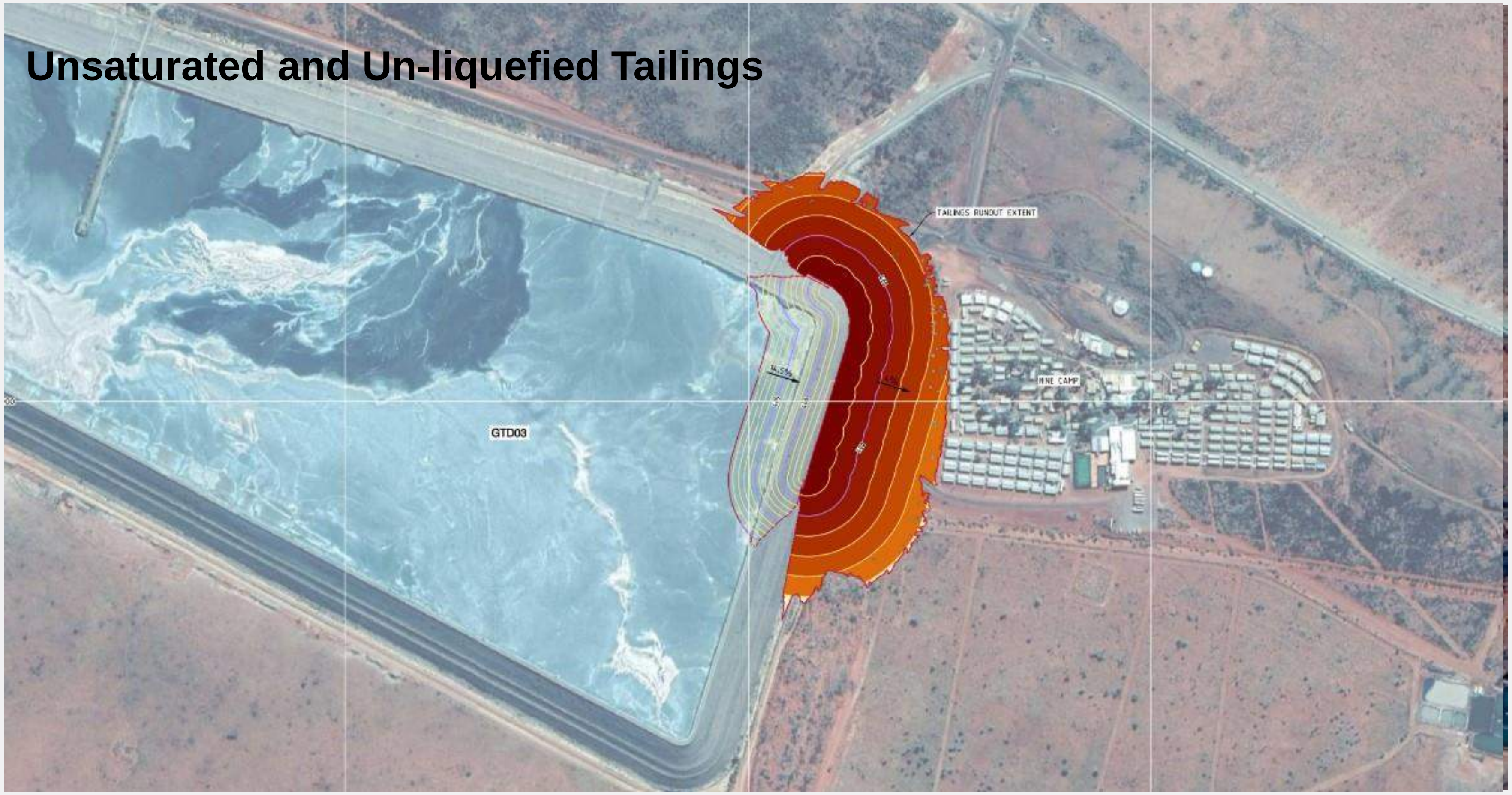
CASE STUDY 2



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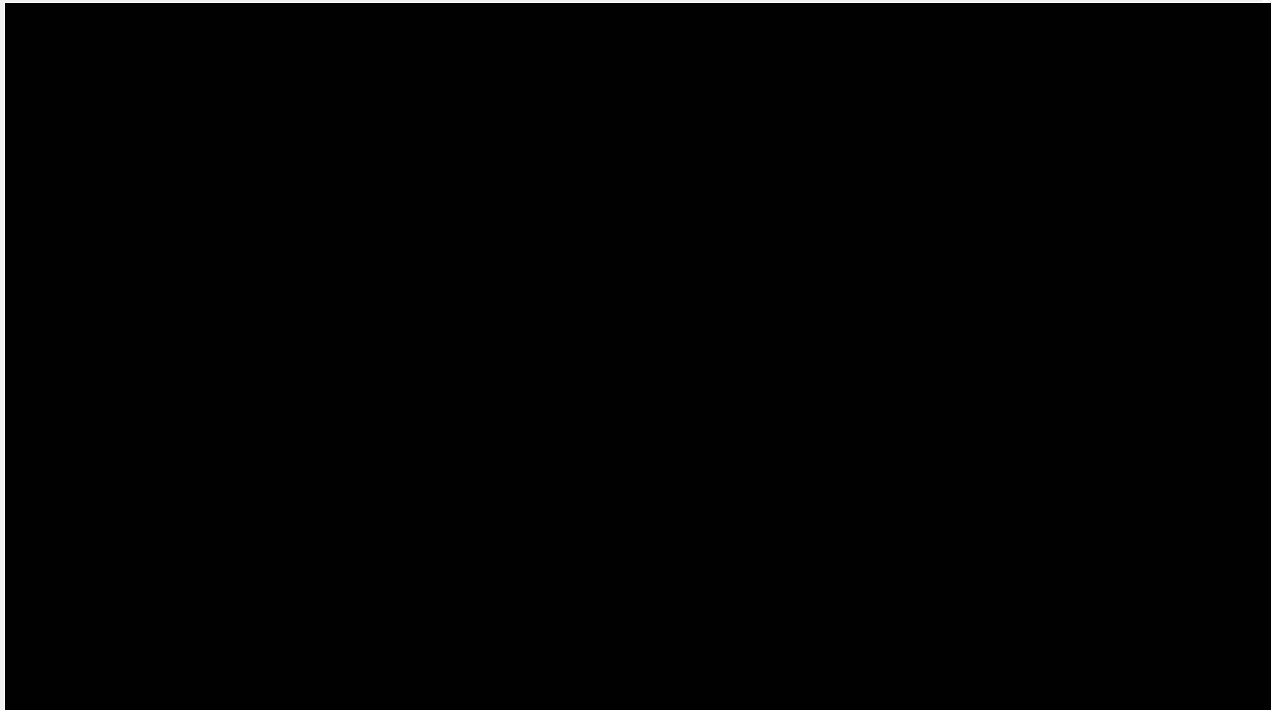
Scenario 1:
Volume Released =1.1Mm3
Yield Stress = 500Pa
Viscosity = 0.1 Pa.s

Low yield stress

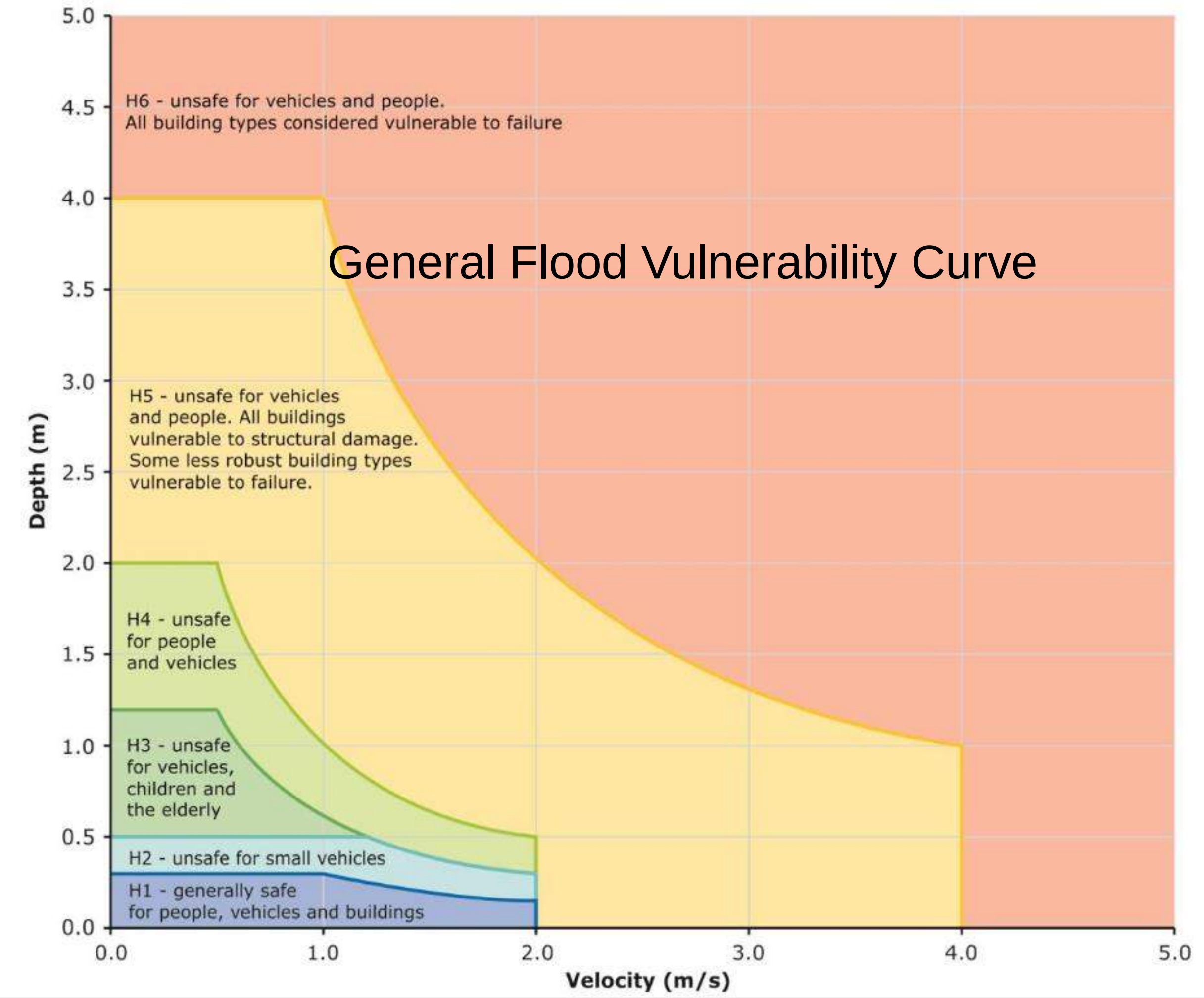
Scenario 2:
Volume Released =1.1Mm3
Yield Stress = 5000Pa
Viscosity = 1 Pa.s

High yield stress



OUTPUT PRESENTATION

- **Inundation maps**
  - Maximum depths
  - Maximum velocities
  - D x V hazard classification
  - Flood arrival time
  - Flood propagation
- **Consequence Category**
  - PAR
  - PLL



Australian Institute for Disaster Resilience (2014), Technical Flood Risk Management Guideline: Flood Hazard, Guideline 7-3

(6)

UNCERTAINTIES IN INPUT PARAMETERS AND SENSITIVITY ANALYSIS

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UNCERTAINTIES IN ESTIMATION OF TAILINGS PROPERTIES AND DAM BREAK PARAMETERS

- Tailings In-situ Density,
- Post-Liquified Shear Strength,
- Rheological Properties of Tailings (Yield Stress and Viscosity)
- Breach mechanism, Geometry and Outflow Hydrograph

Recommendation:
Always undertake a sensitivity analysis to see the impact of variations in the input parameters on the tailings dam break analysis and results.

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THANK YOU

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