The consequences of liquefaction on the failure of tailings dams with particular respect to the upstream construction method

- preliminary reflections on the failure of the Brumadinho iron ore tailings dam in January 2019

Mike Cambridge
Managing Director, Cantab Consulting Ltd

Rafael Monroy
Principal Civil/Geotechnical Engineer, Wood

Darren Shaw
Associate, Water (Dams and Reservoirs), Arup

Contents

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Darren Shaw, Arup
Rafael Monroy, Wood

Tailings: their source and production

- By-product of extractive industry (e.g. gold, copper, iron)
- Ore extracted from mine (open pit or underground)
- Ore crushed and ground to typically fine sand/silt size
- Mixed with water to create a slurry
- Selected metals extracted in an industrial process
- Waste slurry, the ‘tailings’ stream, deposited into storage facilities
- Solids settled out and water recovered for re-use in the process
- Storage generally considered to be indefinite
- Tailings generally contain potential contaminants

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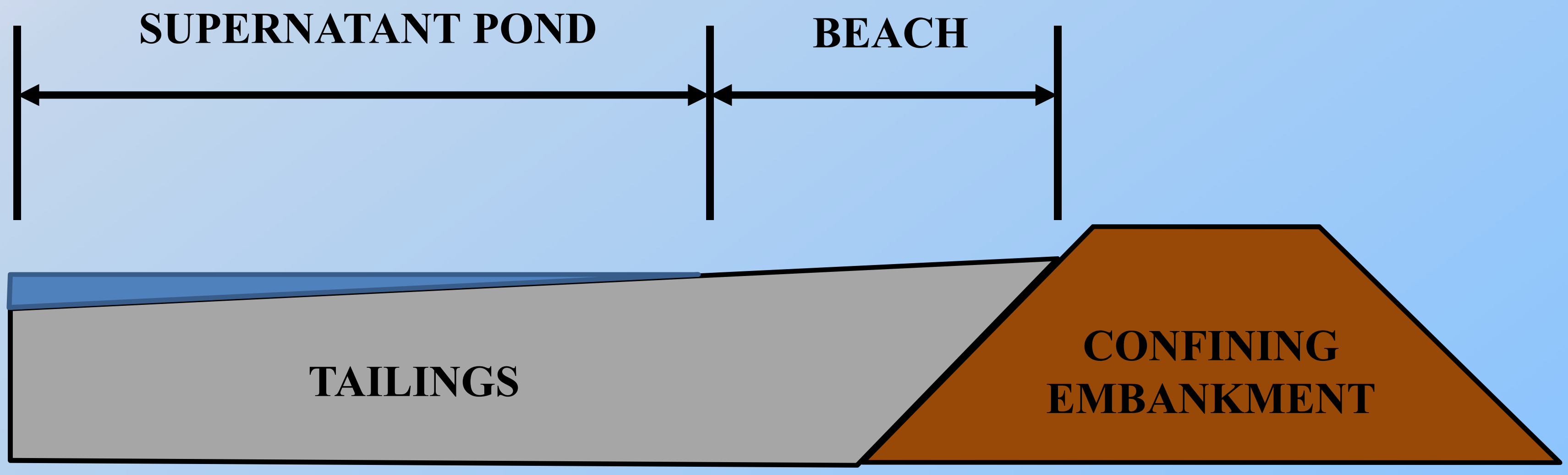
Terminology



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Deposition Methods

- Single point deposition
  - Simple to install and operate
  - Limited control over beach development
  - High energy - limited control over sedimentation
- Spiggoting
  - Multiple discharge points
  - Good control over beach profile and pond location
  - Reduced energy - improved sedimentation
- Spray bars
  - Multiple spray locations
  - Good control over beach profile and pond location
  - Very low energy at discharge – optimum sedimentation
  - More complex to install and operate

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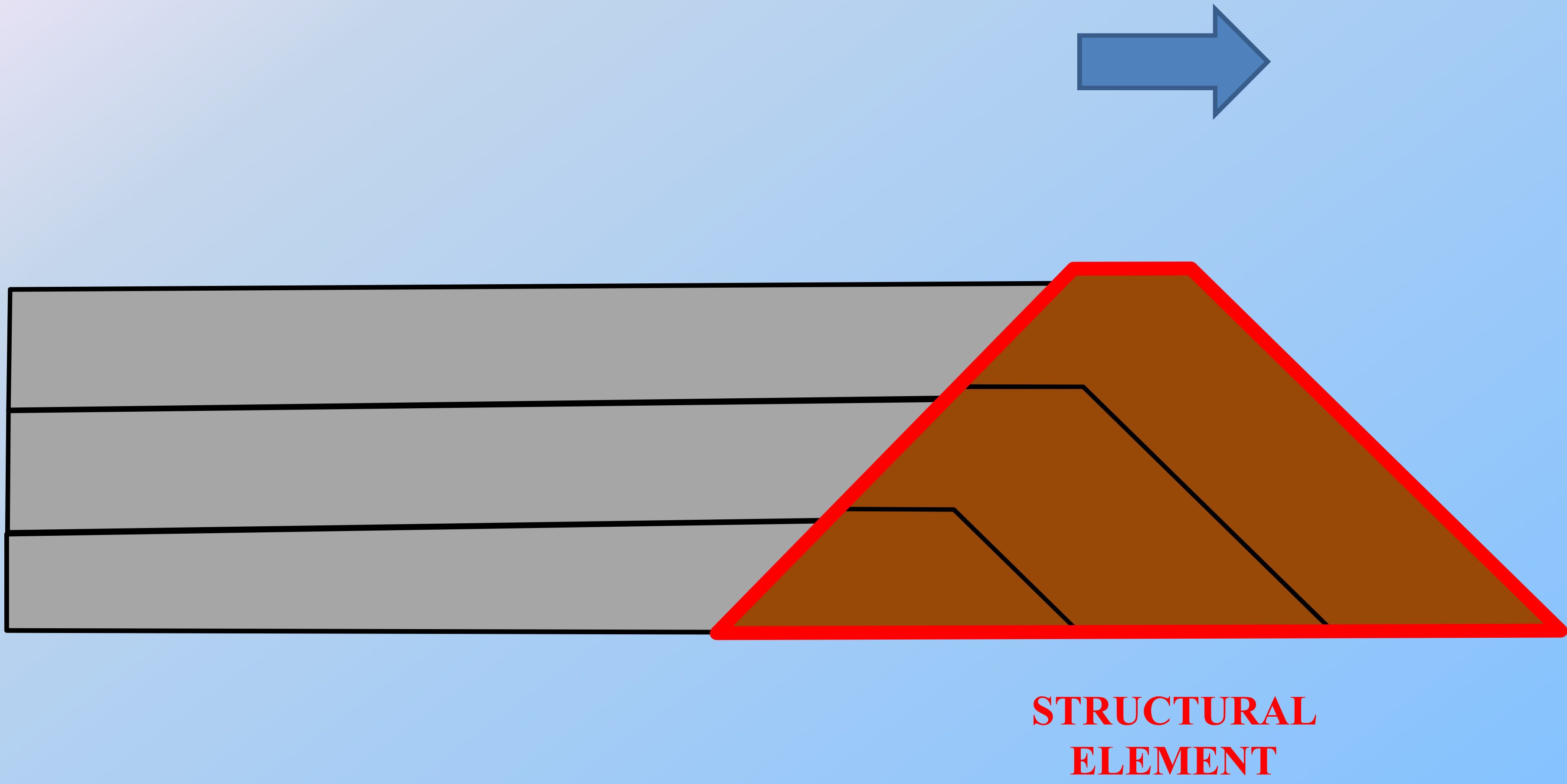
Downstream construction



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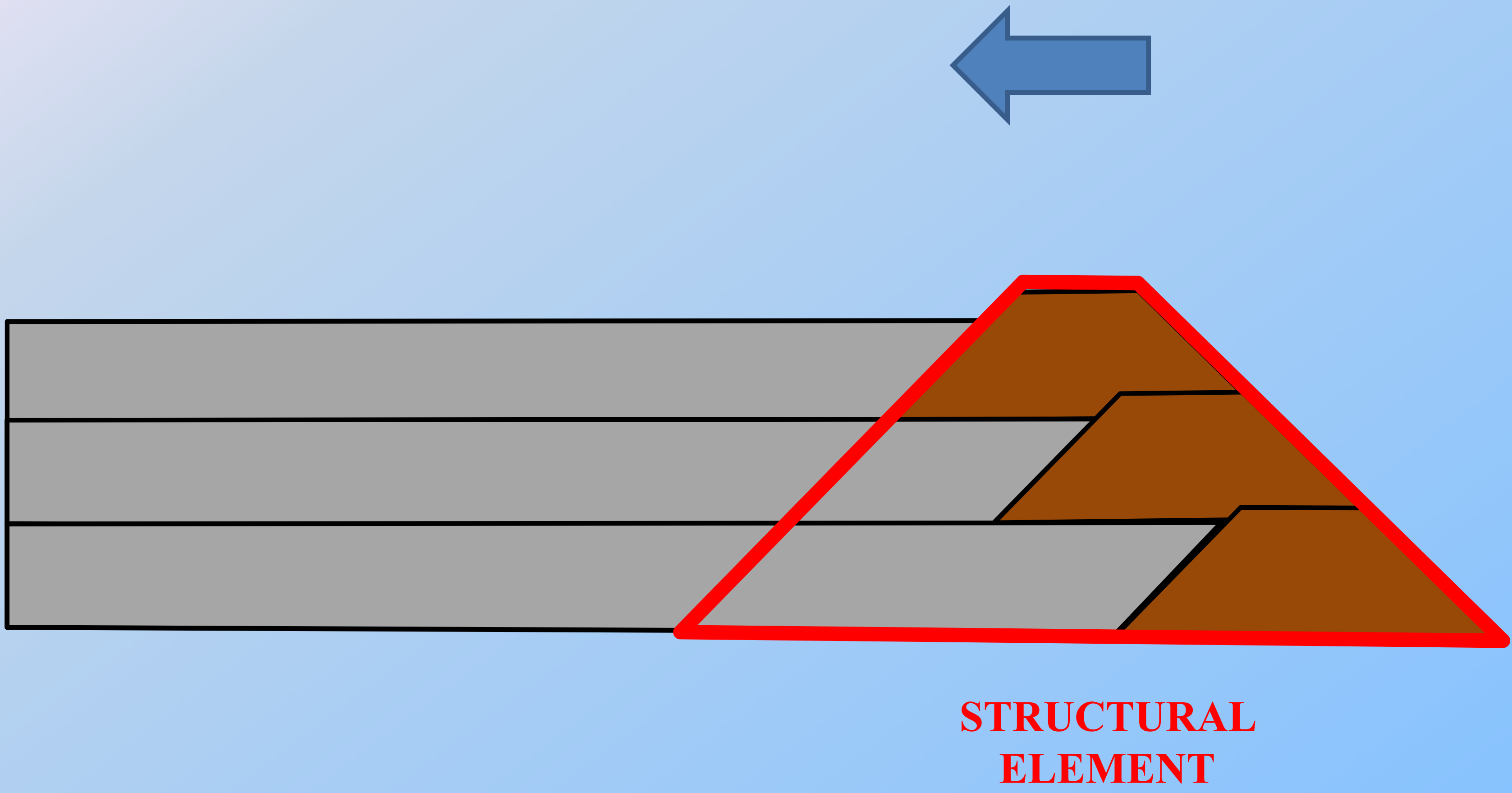
Upstream construction



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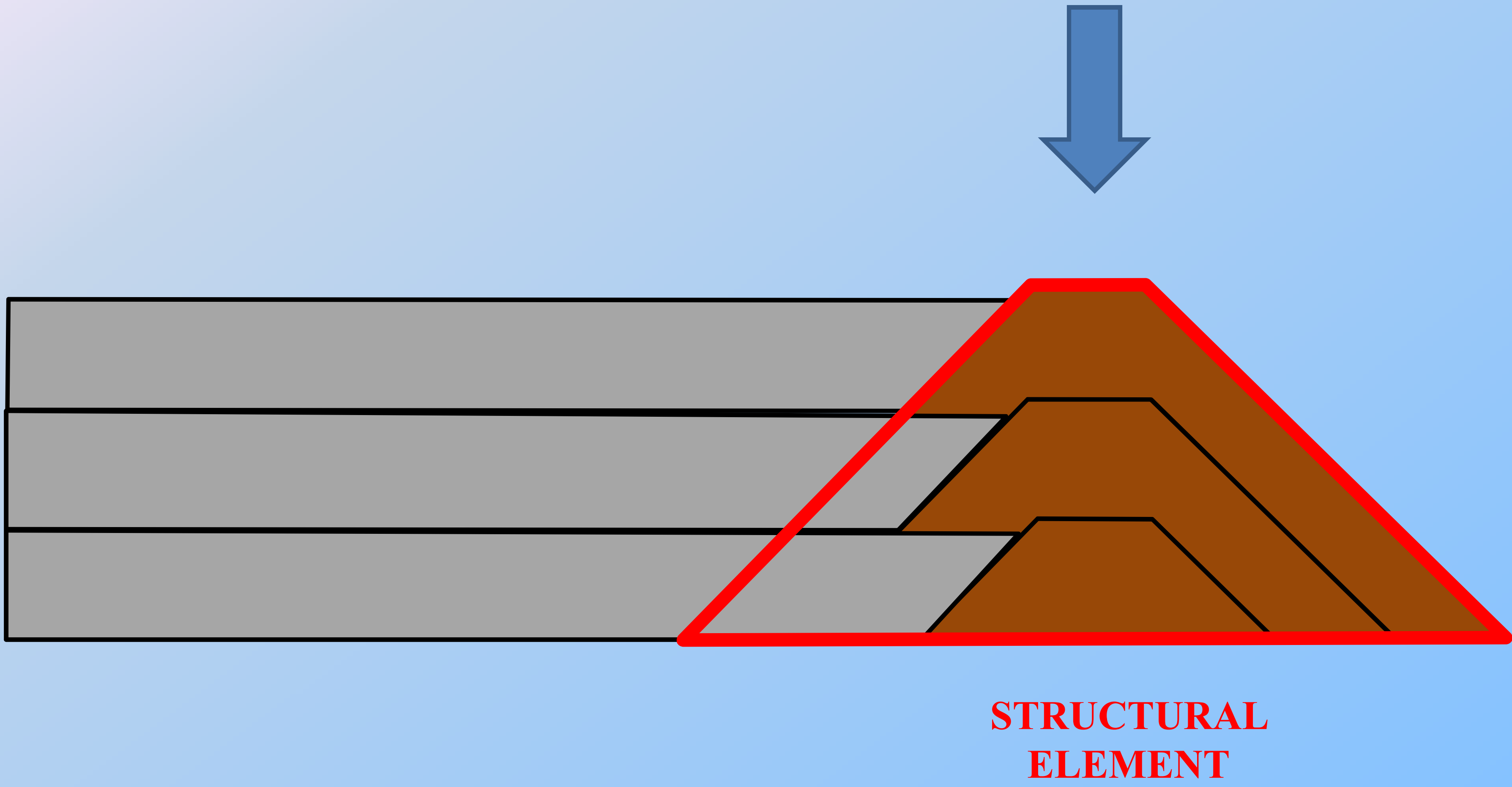
Centreline construction



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Other key design and operational considerations

- Managing deposition to deposit coarse tailings close to the embankment:
  - Improved strength for construction
  - Improved drainage and lower phreatic surface
  - Improve stored density and environmental performance

- Testing strength of tailings beach for upstream and centreline construction

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Other key design and operational considerations

- Underdrainage:
  - Dewatering
  - Reduces phreatic surface at the embankment
- Management of pond size and location:
  - Maximises beach area
  - Increases desiccation rates
  - Reduces phreatic surface at the embankment
  - Reduces risk of overtopping events

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Other key design and operational considerations

Development of the facility over a number of years. Possible changes :

- **Processing rate and rate of rise of the facility**
- **Tailings particle distribution**
- **Slurry water content**
- **Geochemistry**
- **Regulations**

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Soil liquefaction (Rafael Monroy)

“A state official told Reuters that all evidence suggested the dam burst was caused by liquefaction - a process by which a solid material such as sand loses strength and stiffness and turns to liquid.”

BBC (1 February 2019)

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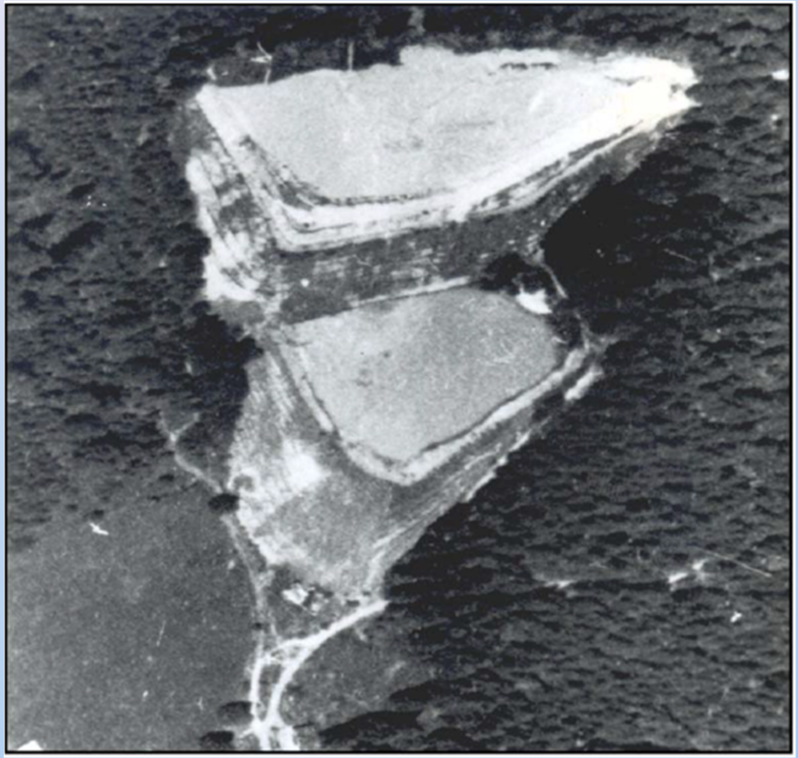
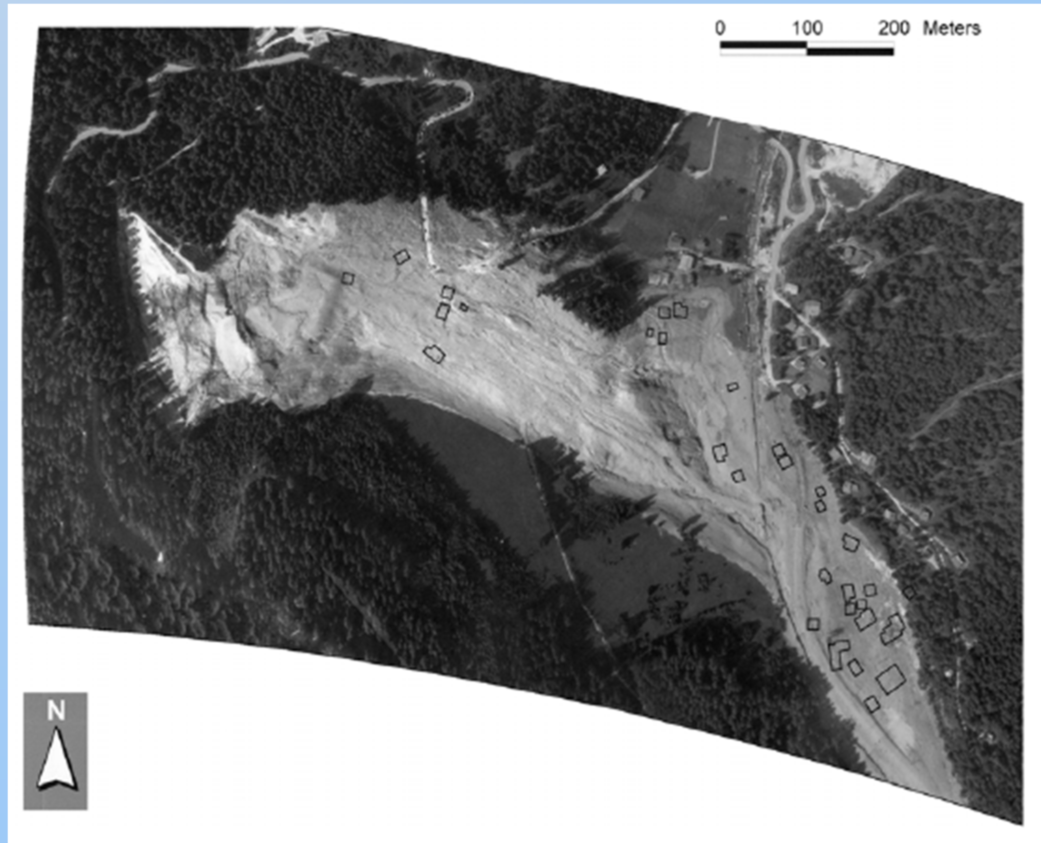
Aberfan (1966)

Stava (1985)





Luino & De Graff (2012)

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Merriespruit (1994)

Fourie & Papageorgiou (2001)

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Aznalcollar (1998)

Alonso & Gens (2006)

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Fundão (2015)

Morgenstern et al (2016)

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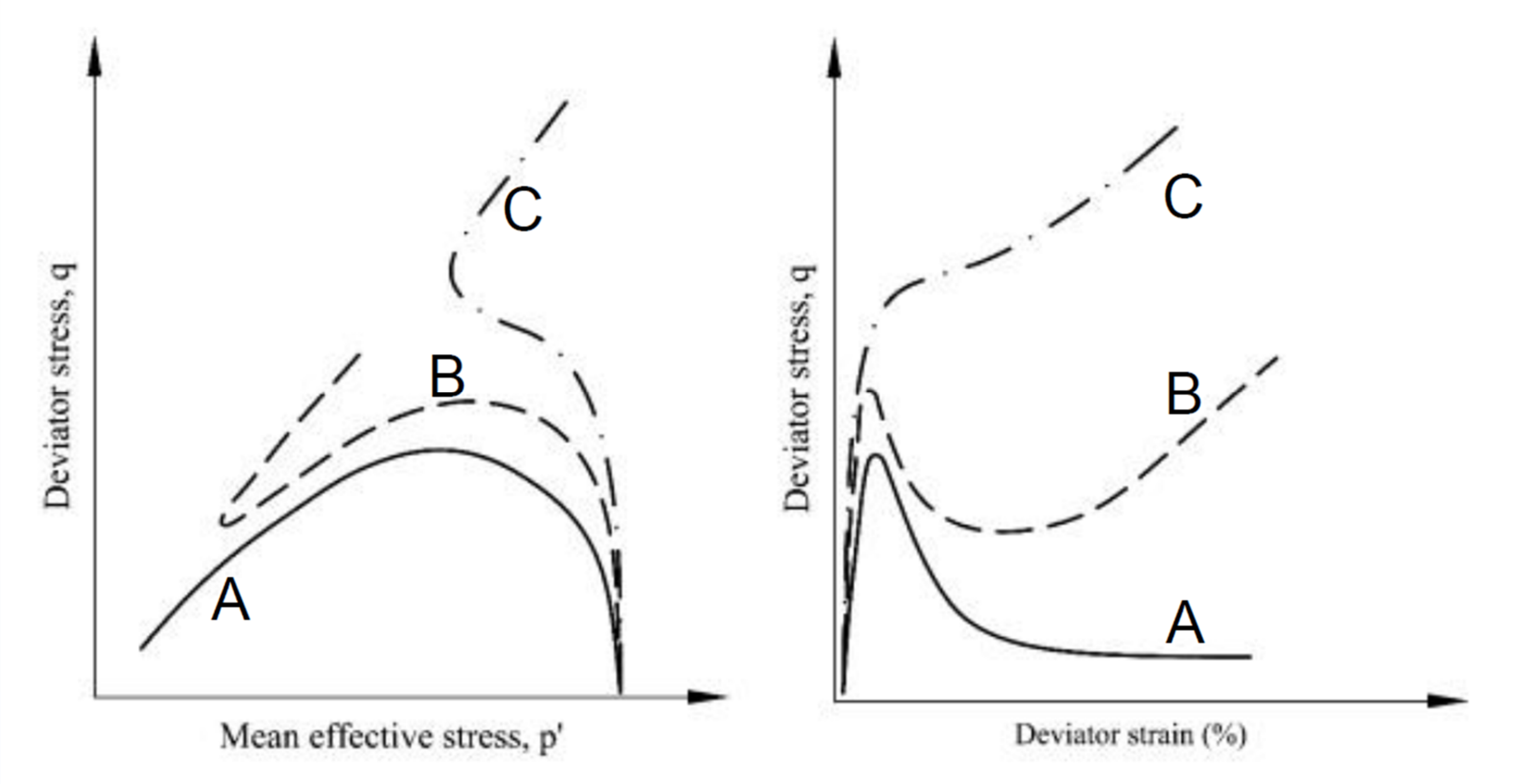
Flow/static liquefaction



Gens (2019)

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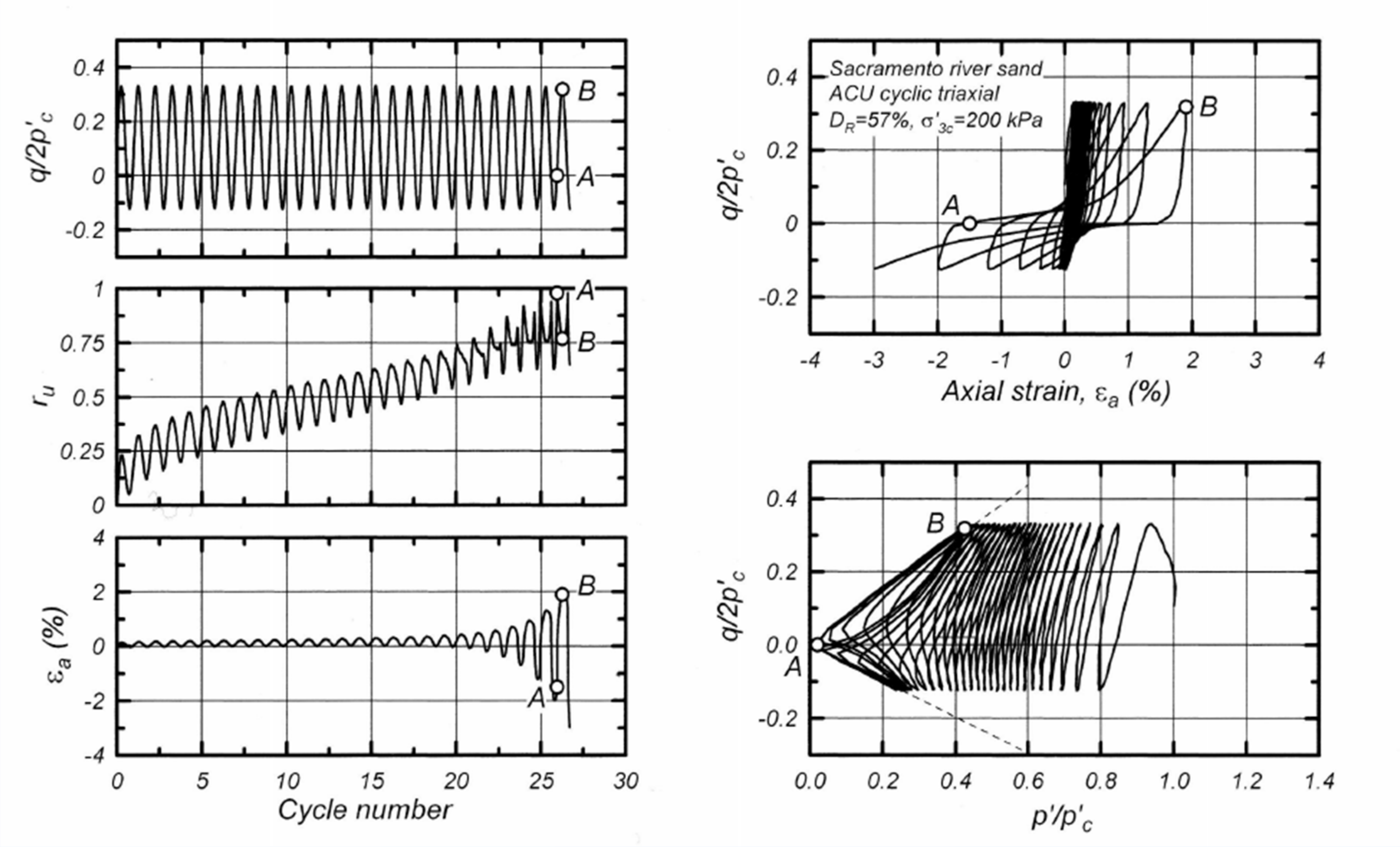
Cyclic liquefaction and cyclic mobility



Idriss & Boulanger (2018)

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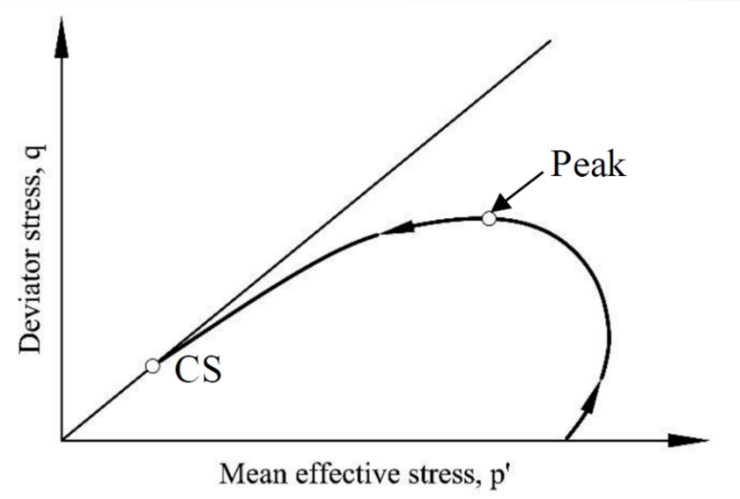
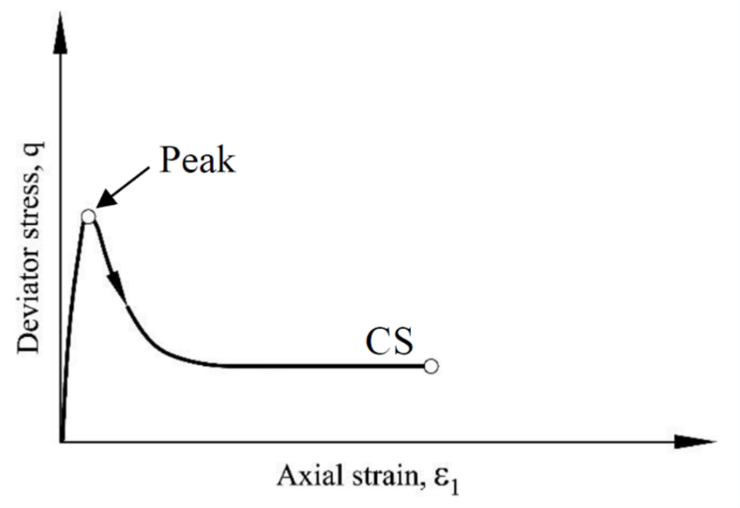
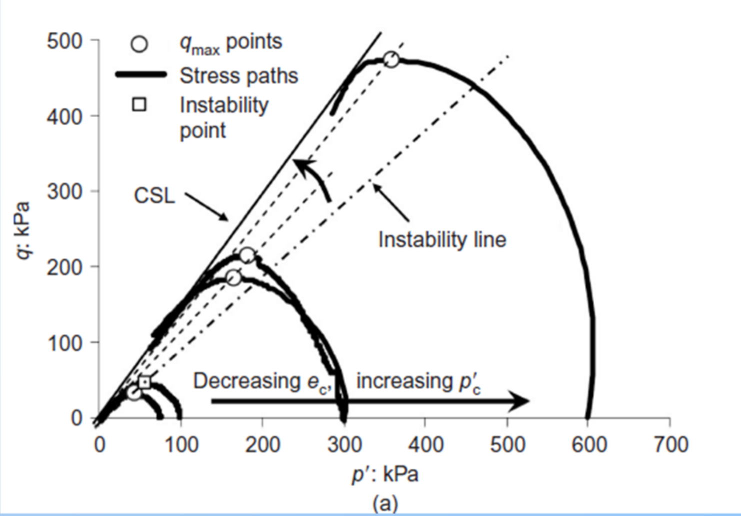
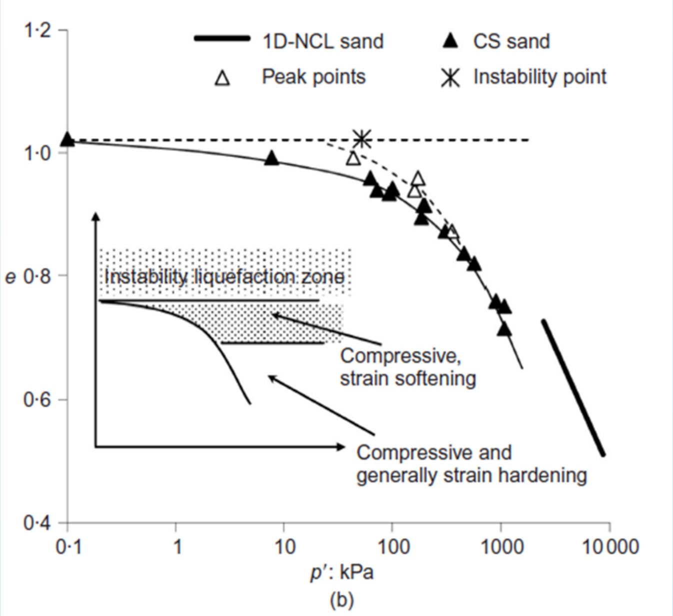
The mechanism of flow liquefaction





Gens (2019)





Carrera et al (2011)

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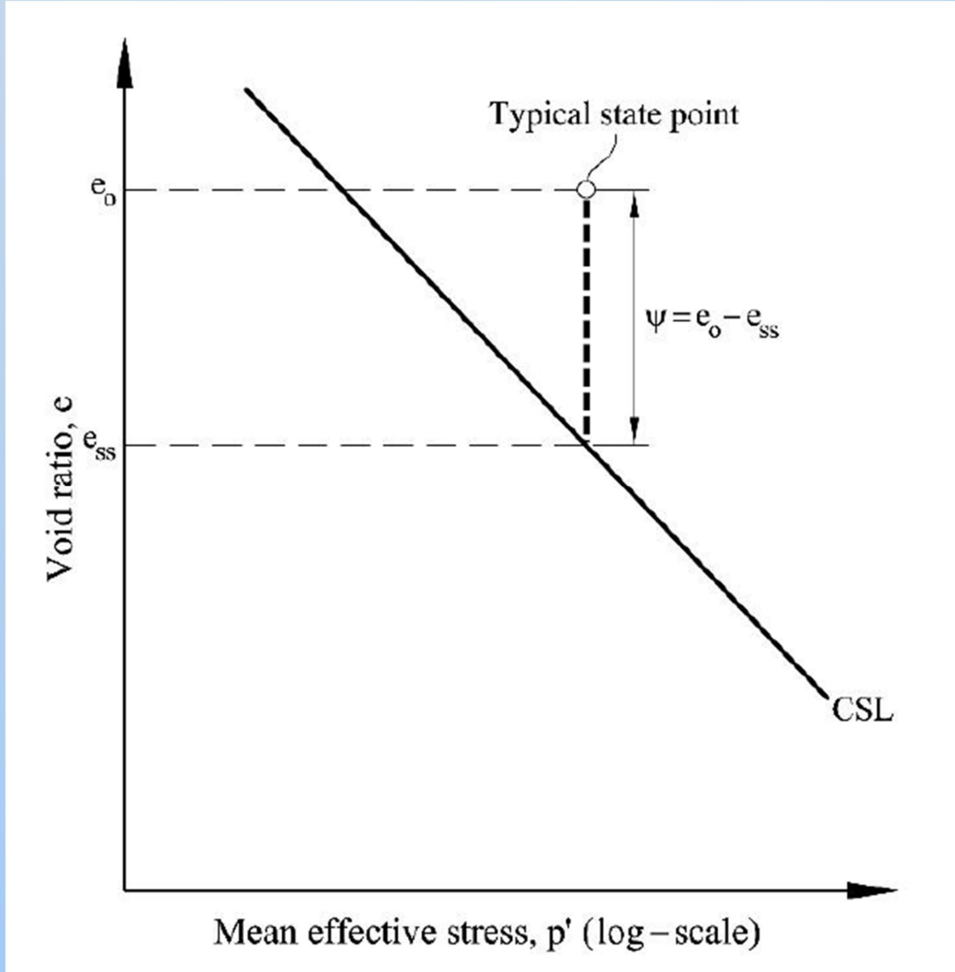
State parameter



Been et al. (1991); in Gens (2019)

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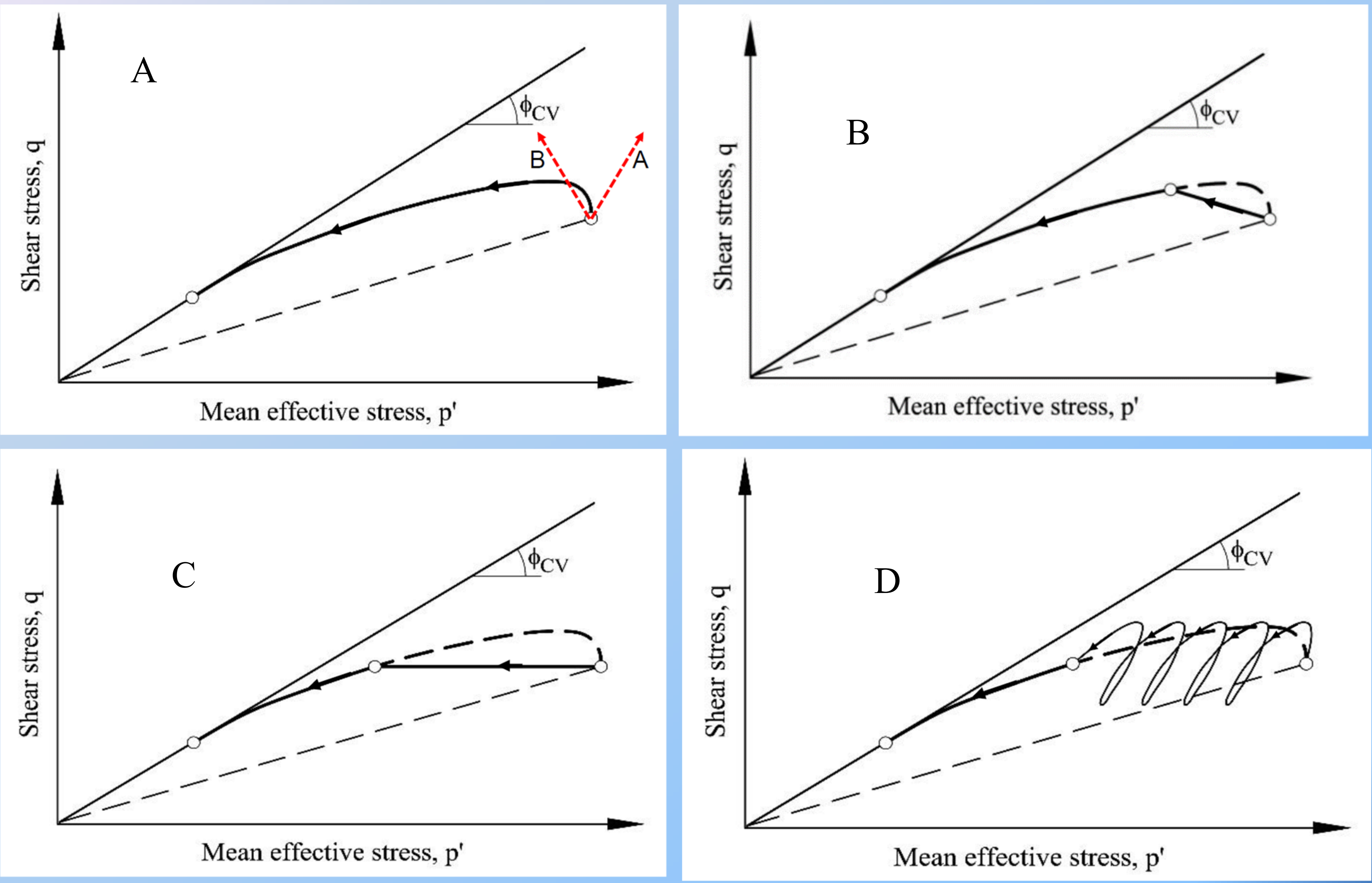
Triggering of flow liquefaction



Gens (2019)

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Changes to guidelines - Australia

"Current recommended guidance is that if the tailings or any other materials, which may be important for the TSF stability, are brittle and potentially contractive, significant rigour is required in the assessment of the liquefaction susceptibility, stability assessment and the triggering analyses."

(ANCOLD 2019 update to Guidelines on tailings dams)

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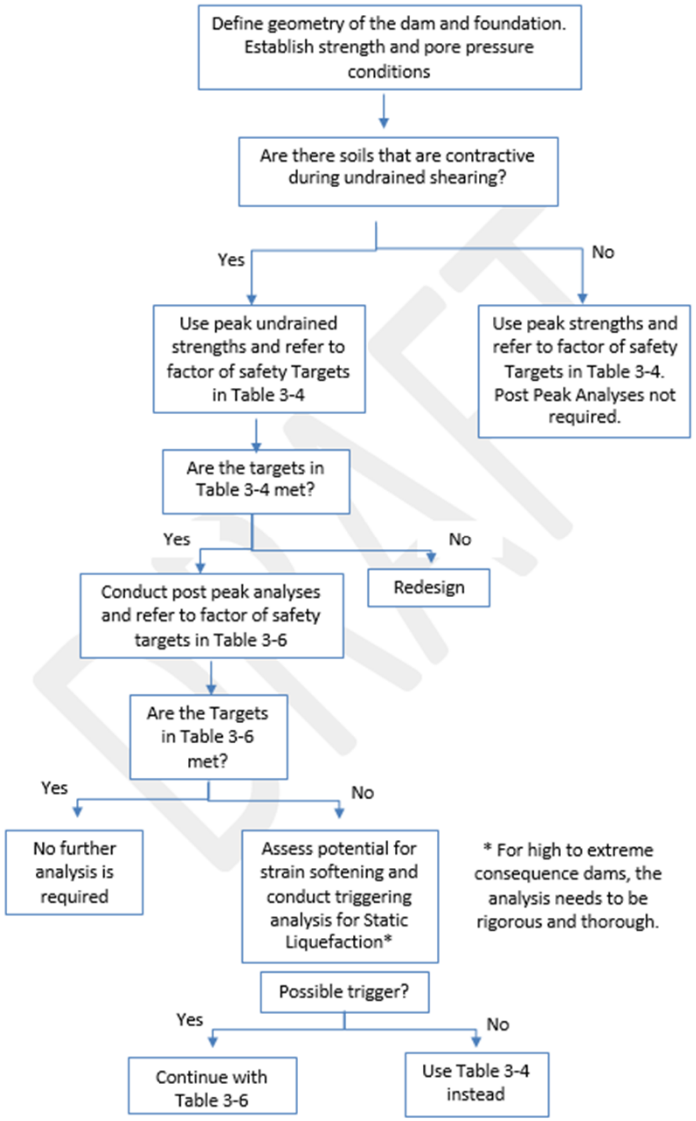
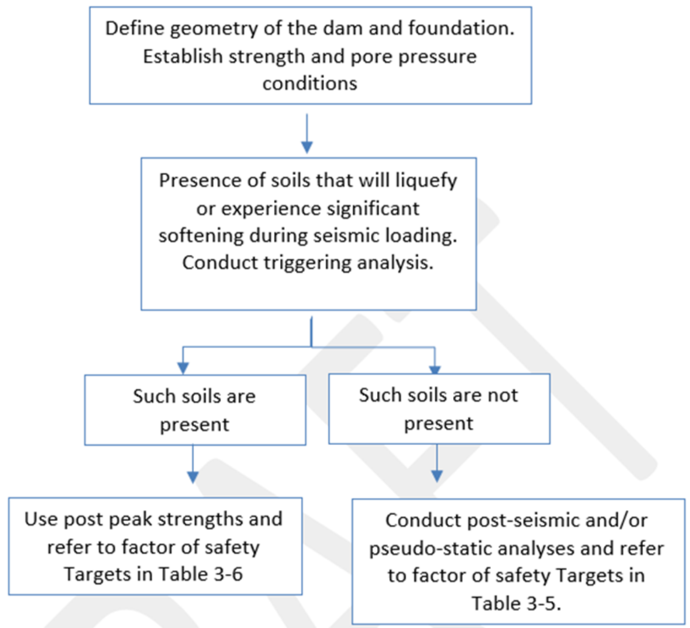
Proposed changes to CDA guidelines - Canada

Figure 3-2 – Stability Analysis Flow Chart – Static Loading Condition
For undrained or partially undrained shearing conditions



CDA (2019)

Figure 3-3 – Stability Analysis Flow Chart – Seismic Loading Condition



CDA (2019)

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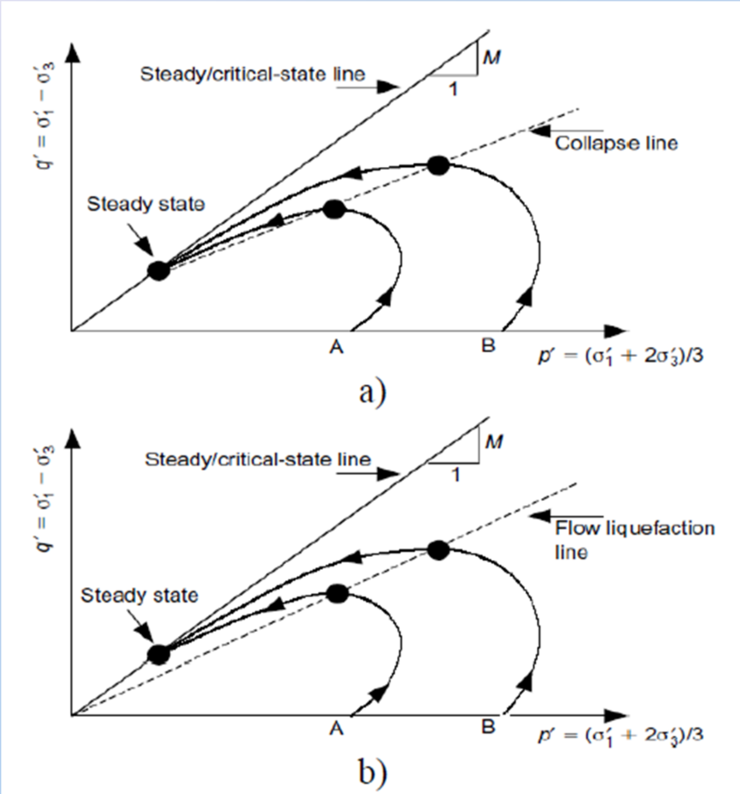
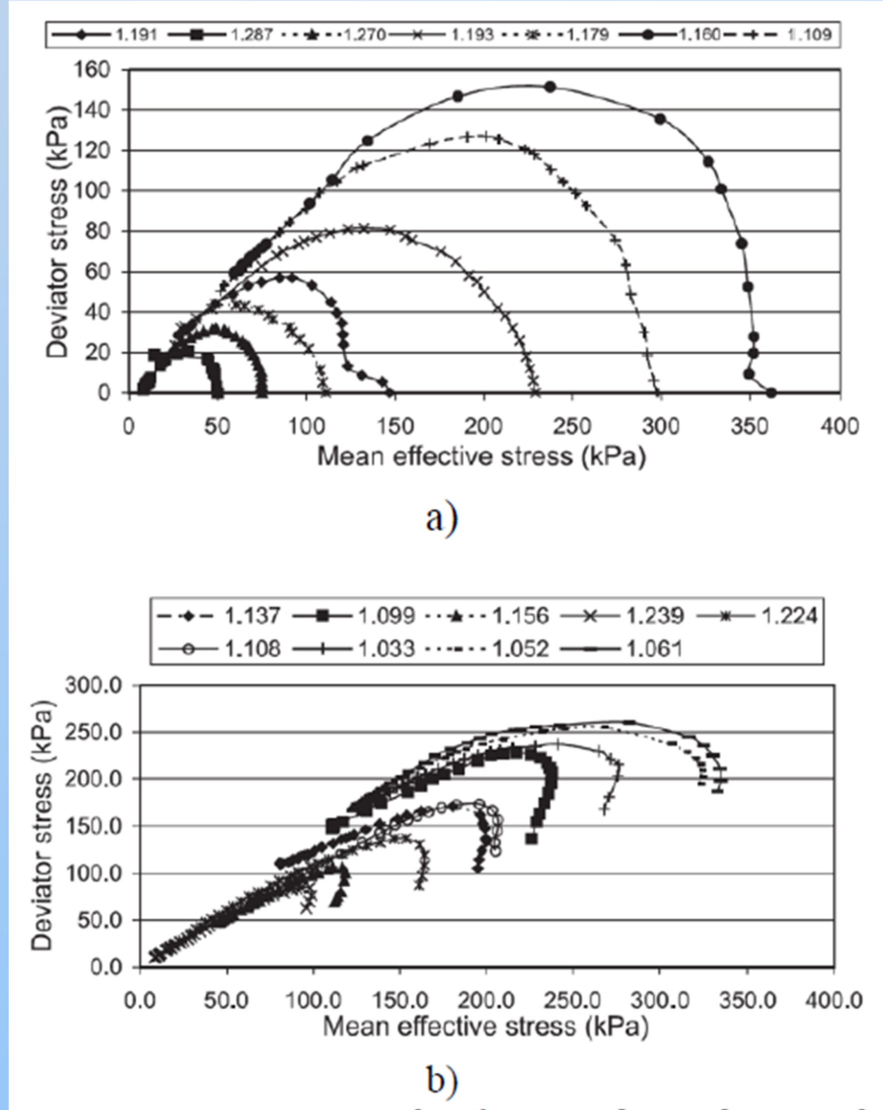
Assessment of peak and critical state strengths



Yang (2002), in Gens (2019)



Fourie and Tshabalala (2005), in Gens (2019)

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"…there is nothing wrong with upstream tailings dams provided that key principles are adhered to in the design, construction, and operation of such dams… I advocate for purposes of preliminary design that liquefiable deposits that can liquefy be assumed to do so..."

Morgenstern (2018)

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Brumadinho failure – preliminary geotechnical assessment (Mike Cambridge)

- Project setting
- Legislative background (pre-2019)
- The design, construction and failure of Brumadinho Barragem No. 1
- Parallel failure of Fundão 2015/Cavendish Mill 2007
- Preliminary reflections on the 2019 failure of Barragem No. 1
- The aftermath

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The failure of Brumadinho Barragem No.1 on 25th January 2019

These reflections on the Brumadinho failure are of a preliminary nature as the authors are not party to historical or recent monitoring and investigation data.

The information provided is based on photographic evidence released at the time, on publically available documents and on statements made by Vale (the Owner).

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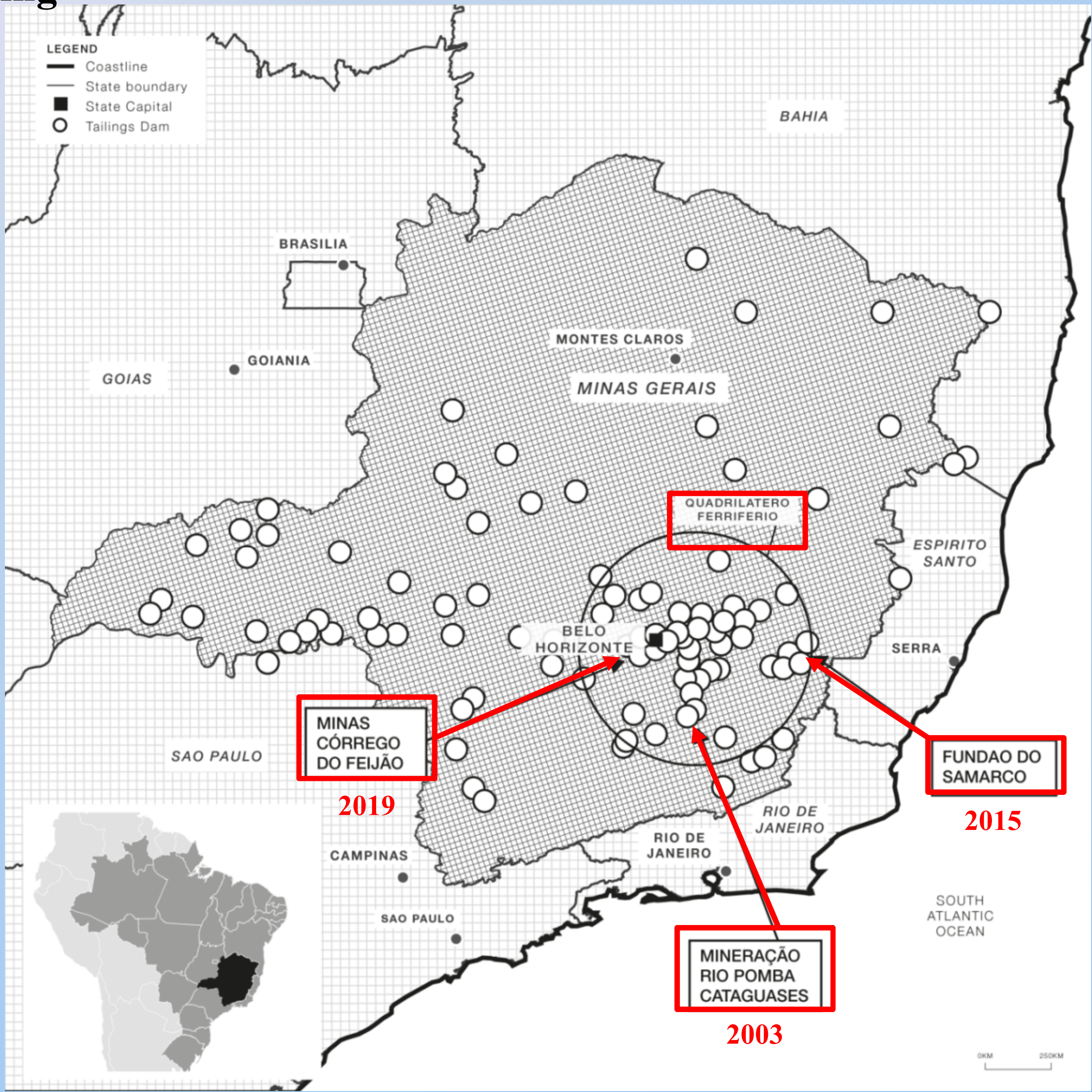
Project setting



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Project setting

- Minas Córrego do Feijão lies within the area known as the Quadrilátero Ferrífero which extends across the south eastern quadrant of Minas Gerais in eastern Brazil.
- Brumadinho Barragem No.1 was a principal production element of the Minas Córrego do Feijão iron ore mine between 1976 and 2015.
- The Quadrilátero Ferrífero region is renowned as a world class producer of iron ore, gold, bauxite and other minerals, and as a result has a very high concentration of tailings dams.
- A large proportion of these dams have been constructed using similar (upstream) techniques to those employed at Brumadinho.
- Brumadinho Barragem No.1 is owned by Vale, which was also part-owner of the Samarco de Fundão Dam which failed in 2015.
- Vale reports that it is responsible for 123 tailings dams within Minas Gerais.
- A 2017 study by the National Water Agency classified more than 700 Brazilian dams as being at high risk of collapse and having significant potential for causing damage.

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Regional context for the failure of Brumadinho Barragem No. 1

Recent dam failures in Brail 2001-2019, (Neves, 2018)

Mine site	Mineral	Year	Dam height	Volume released	No. of deaths	Displaced persons
Mineração Rio Verde	Iron	2001	No data	No data	5	5000
Mineração Rio Pomba Cataguases	Bauxite	2003	No data	$2Mm^3$	0	600,000
Barragem de Camara no Paraibo	Water	2004	No data	$26Mm^3$	5	3000
Algodoes No. 1 Piaui	Water	2009	No data	No data	4	2000
Herculano Mineração	Iron	2014	No data	No data	3	No data
Barragem do Fundão do Samarco	Iron	2015	110m	$60Mm^3$	19	250,000
Brumadinho Barragem No. 1	Iron	2019	86m	$12Mm^3$	+242	Unknown

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Historical dam regulations applicable to mining dams

- Mining legislation in Brazil historically focused on mine permitting which regulation was vested in the National Mining Agency, ANM.

- Law 12.334/2010 defined the following dam characteristics:

  "a) Height of the dam from the lowest point of the foundation to the crest greater than or equal to 15m (fifteen metres);
  b) Total reservoir capacity greater than or equal to 3,000,000m³ (three million cubic metres);
  c) Reservoir containing hazardous waste in accordance with applicable technical standards;
  d) Medium or high potential associated damage (APD) category, in economic, social, environmental or loss of life terms, as defined in art. 6th."

- Resolution No. 143/2012 provided the classification framework to be adopted by the regulatory agencies (ANEEL (water dams) and ANM (mining dams)) with the dams being classified by:
  a) "the inspection agents by risk category, associated potential damage and their volume, based on general criteria established by the National Water Resources Council (CNRH).
  b) the classification of potential damage associated with the dam as high, medium or low being based on the potential loss of human life and the economic, social and environmental impacts."

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Regulation following the 2015 failure of the Barragem do Fundão do Samarco

- **A review of both mining regulations and of dam safety was undertaken by the Brazilian Government with the aim of preventing future disasters.**

- **The review culminated in a new regulatory regime and, in 2017, in the National Mining Agency, ANM being reconfigured.**

- **Between 2018 and February 2019 a new regulatory regime was brought into force targeting the safety of tailings dams in the knowledge that many facilities had the same characteristics as that which had failed at Fundão do Samarco.**

- **This regime categorised dams by size and by risk to the downstream population and initiated the following:**
  a) **a more formal system of inspection and reporting;**
  b) **detailed design and construction checks;**
  c) **preparation of emergency action plans.**

- **However:**

ANM indicated that it had inadequate resources to effect appropriate oversight of the inspection and reporting regime given the number of potentially at-risk facilities in the State.

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Minas Córrego do Feijão, Brumadinho Barragem No.1

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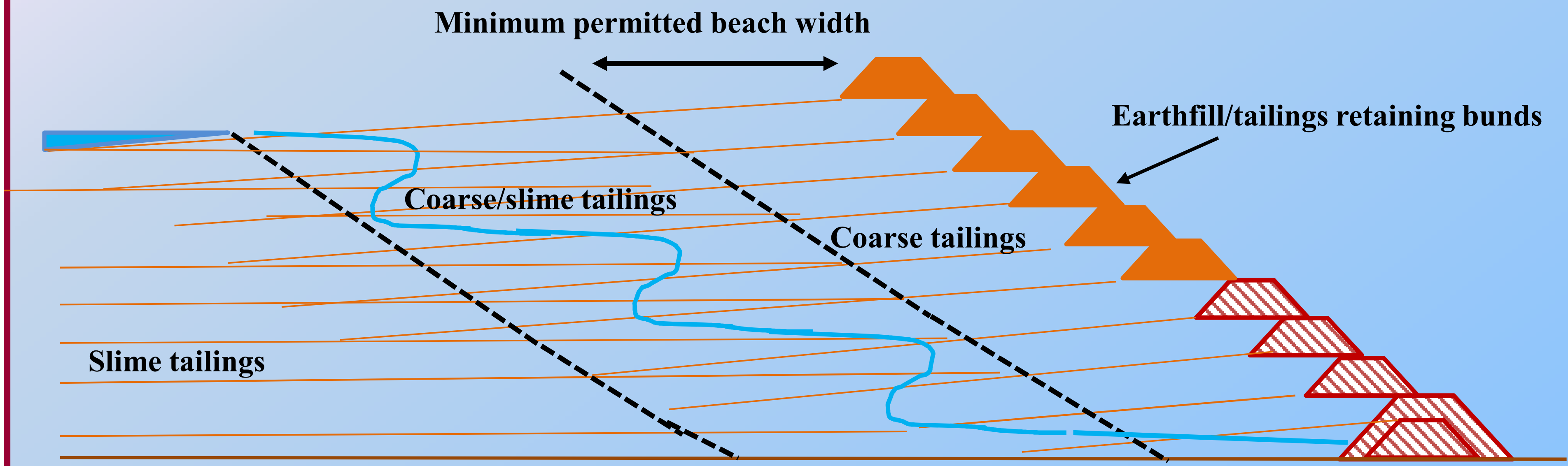
Brumadinho Barragem No.1 - inferred design section



- The final proposed dam height was 87m.
- The storage capacity of was 12Mm^3.
- 94 piezometers were installed.
- Mining facilities appear to have been under continuous video surveillance.
- The dam section did not include a rock toe or , it appears, formal internal drainage provisions.
- Construction commenced in 1976 with final crest height achieved in 2010.

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Brumadinho Barragem No.1

Deposition is reported to have ceased in 2015, though this dam may well have subsequently been used for water storage.

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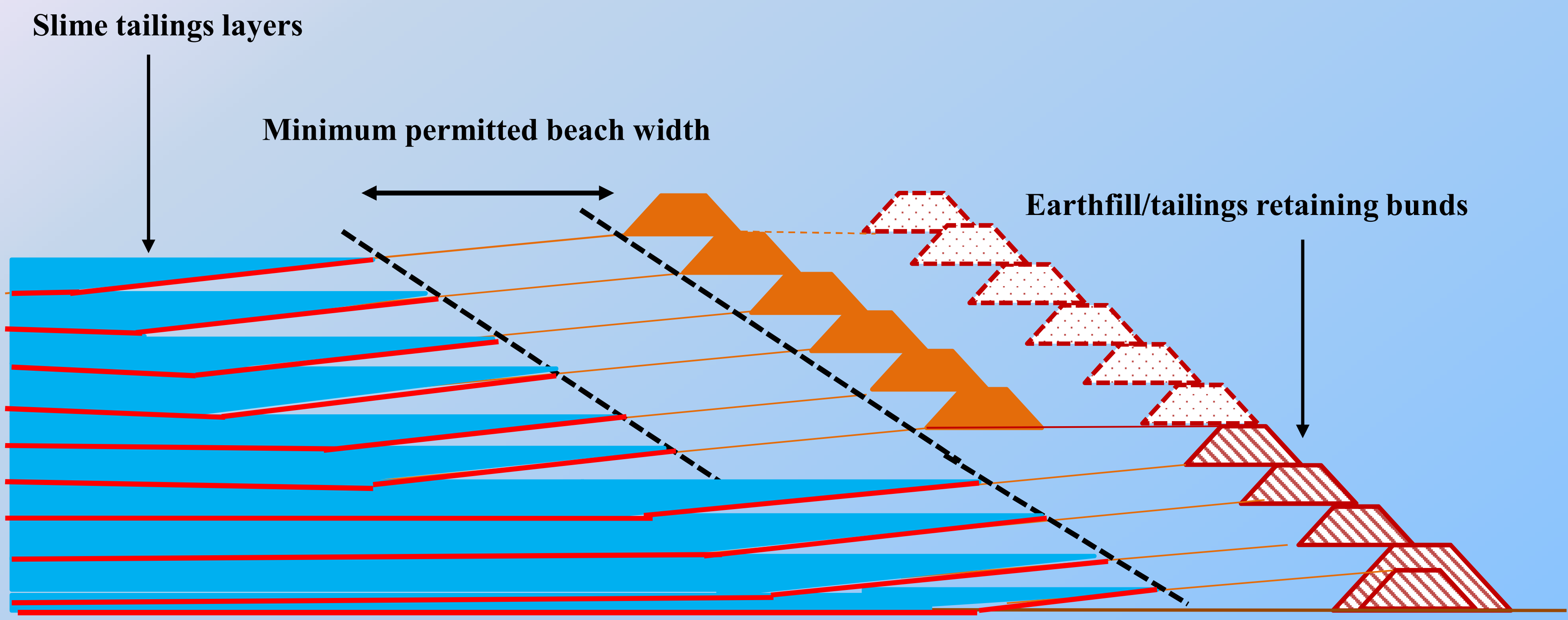
Brumadinho Barragem No.1 - modified design section



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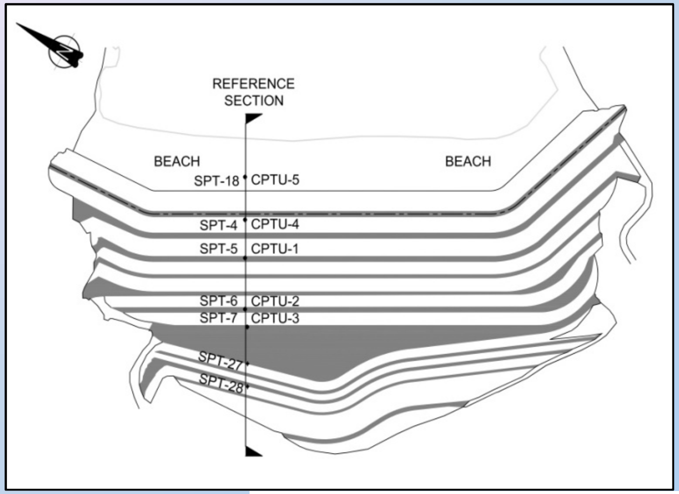
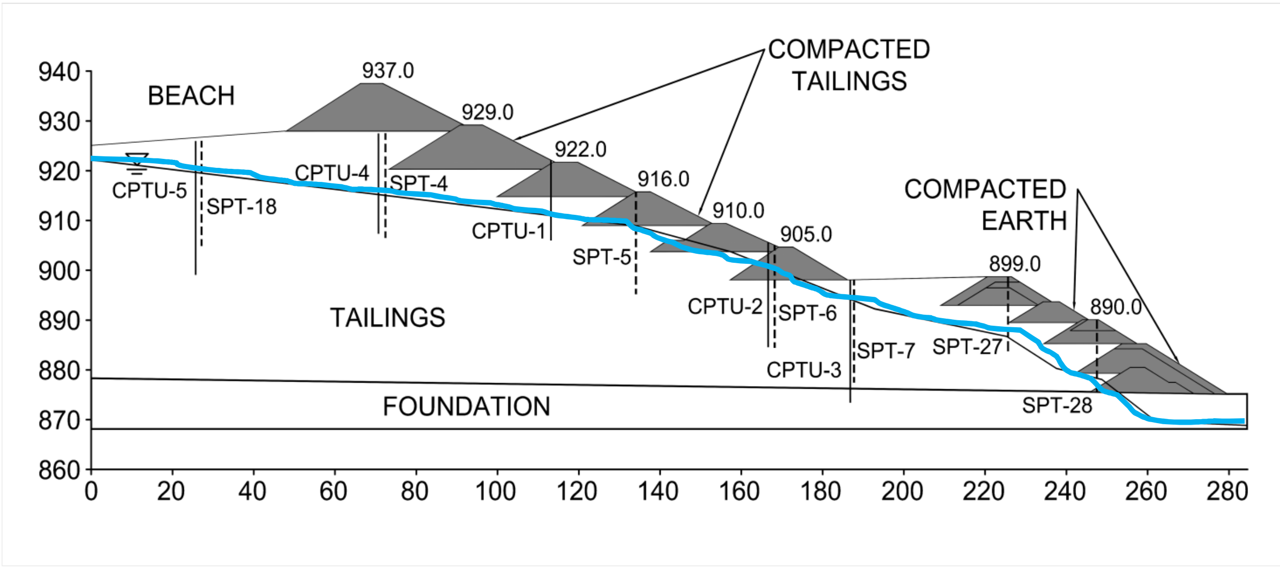
Brumadinho Barragem No.1, 2010 site investigation





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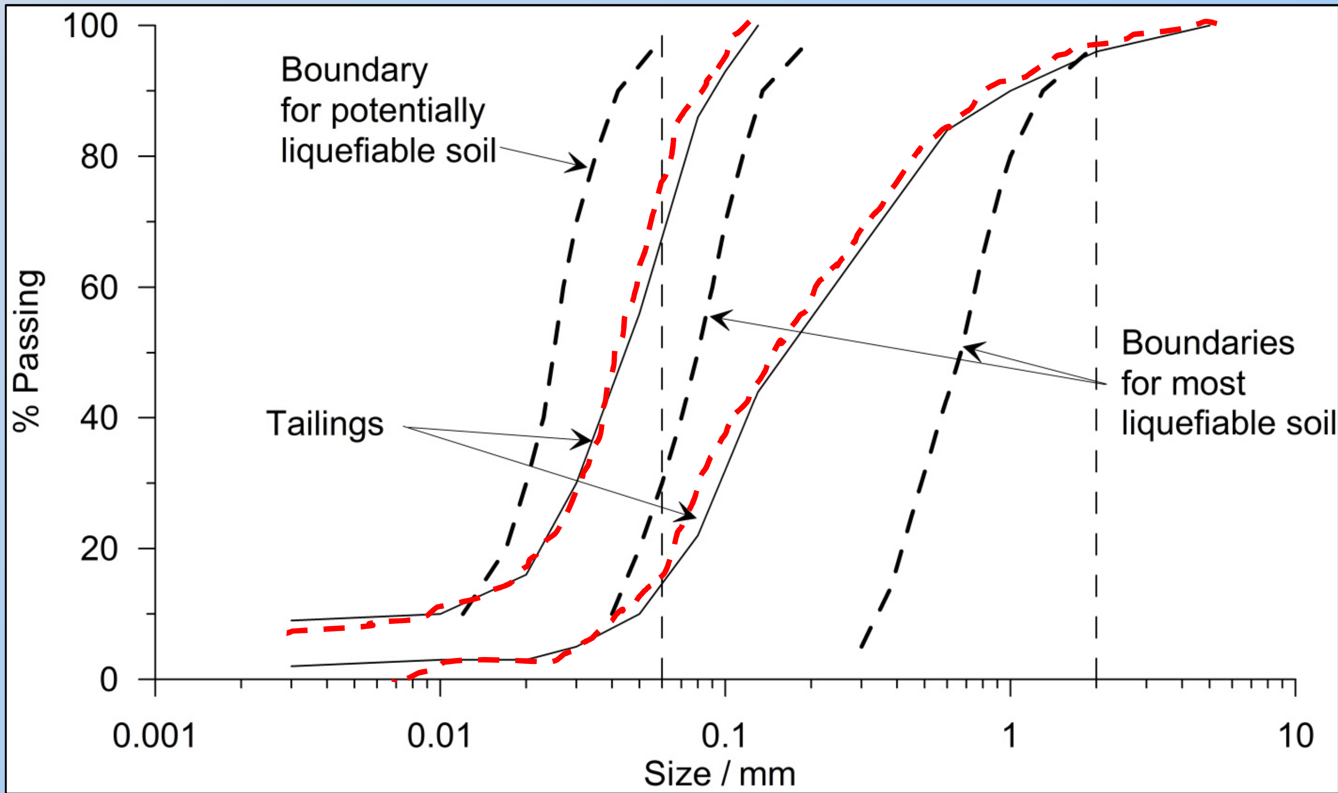
Brumadinho Barragem No.1 - summary results of the 2010 site investigation



Boundaries for liquefiable soils, after Tsuchida

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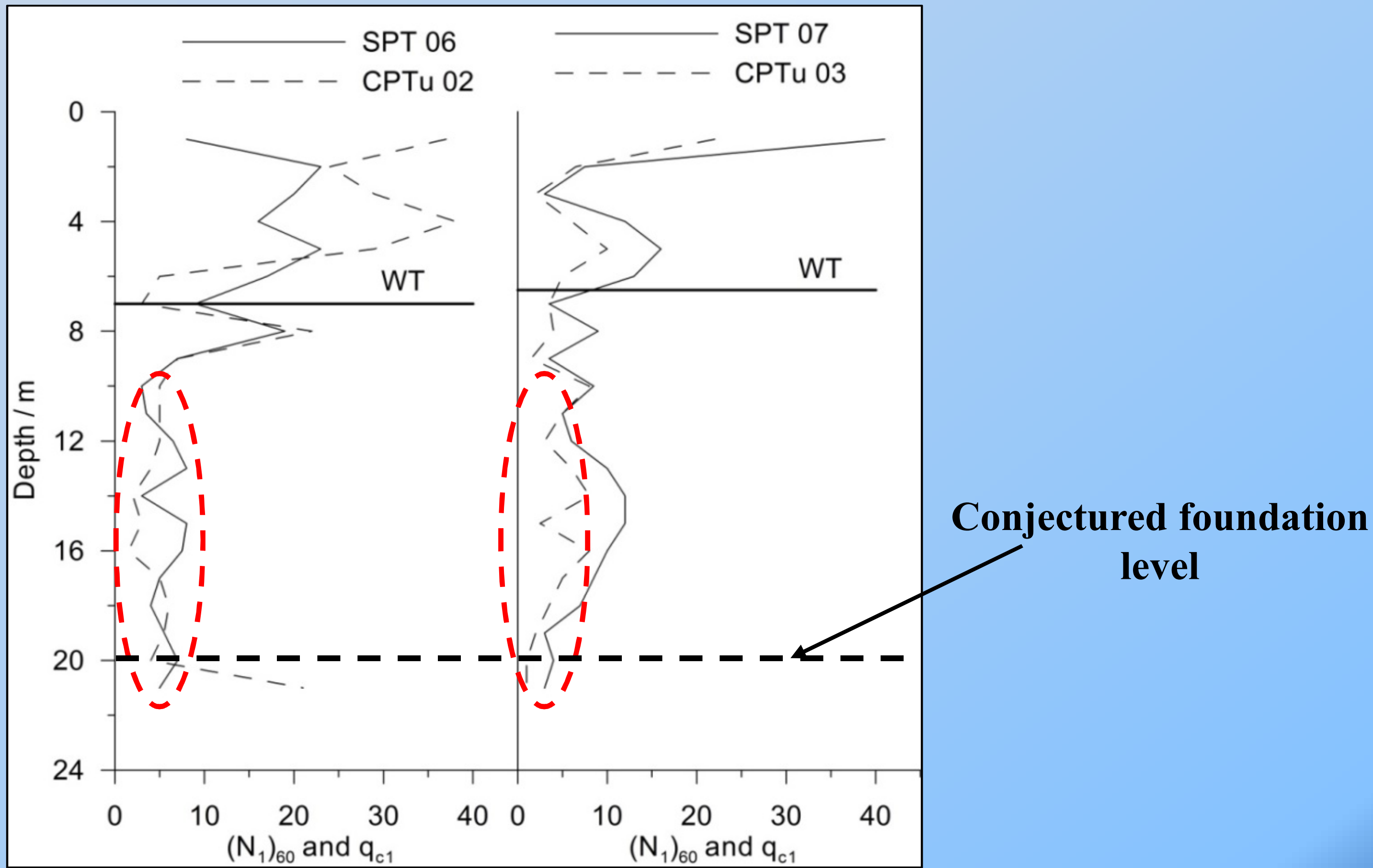
Brumadinho Barragem No.1 - summary results of the 2010 site investigation



CPT/SPT data from 2010 investigation

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The failure of Brumadinho Barragem No.1 on 25th January 2019

12.28.26

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The failure of Brumadinho Barragem No.1 on 25th January 2019

12.28.28

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The failure of Brumadinho Barragem No.1 on 25th January 2019

12.28.29

The failure of Brumadinho Barragem No.1 on 25th January 2019

12.28.31

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The failure of Brumadinho Barragem No.1 on 25th January 2019

12.28.44

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The failure of Brumadinho Barragem No.1 on 25th January 2019

12.29.01

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The failure of Brumadinho Barragem No.1 on 25th January 2019

- **The liquefied tailings flowed through the mine site, engulfing mine infrastructure and downstream settlements and reaching the confluence with the Rio Paraopeba with significant environmental damage.**
- **The current confirmed death toll is 242, though a significant number remain unaccounted for.**
- **In terms of the death toll this incident probably represents the worst tailings dam disaster *for 40/50 years.***

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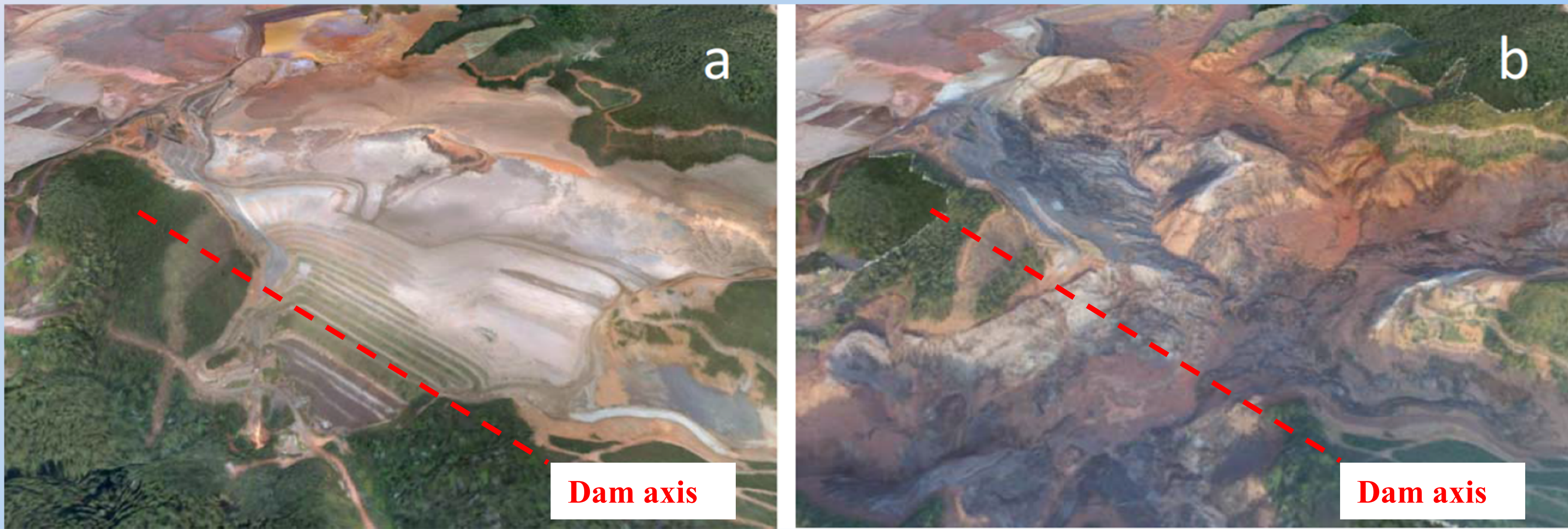
Rafael Monroy, Wood

Parallel failures - Samarco do Fundão Dam in 2015

This Vale/BHP tailings dam failed in 2015 with the loss of 19 lives, the destruction of the town of Bento Rodrigues and the pollution of 600km of the Rio Doce.



The Fundão tailings dam investigation - report summary

- **"the slimes beneath the embankment responded to the increasing load being placed on them by the rising embankment**
- **as the softer slimes were loaded, they compressed and deformed laterally, squeezing out like toothpaste from a tube in a process known as lateral extrusion**
- **the sands immediately above, forced to conform to this movement, experienced a reduction in the horizontal stress that confined them"**

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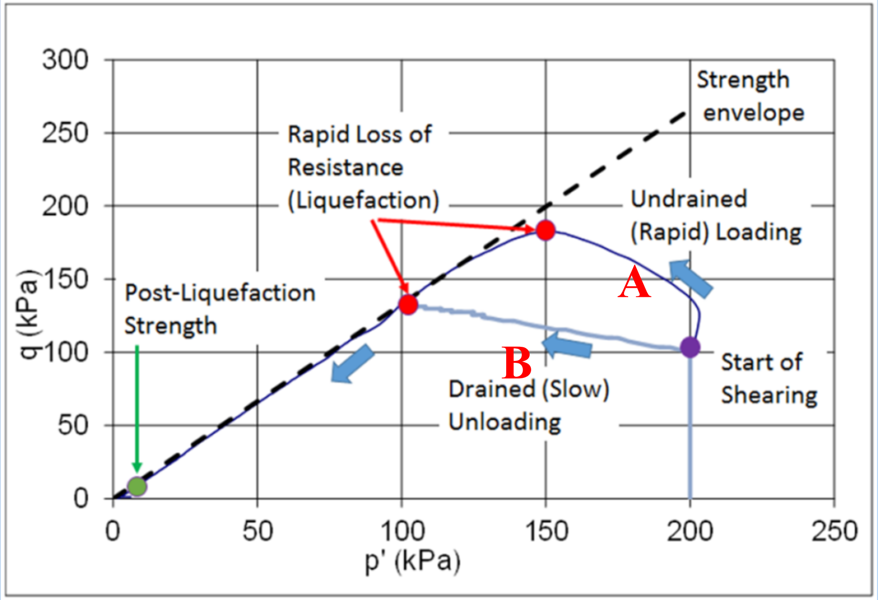
Parallel failures - Samarco Fundão Dam in 2015



Triaxial tests on the Fundão tailings were designed to assess the response during undrained loading and drained unloading:

- **Test A: undrained loading to simulate rapid shearing – as the stress path reaches the strength envelope it experiences a dramatic reduction in strength.**
- **Test B: sample laterally unloaded at a slow rate to ensure drained conditions - as the stress path reaches the strength envelope strength rapidly decreases.**
- **Post-liquefaction (critical) strength is the same in both cases.**

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Rafael Monroy, Wood

Parallel failures - Samarco Fundão Dam in 2015

Report summary of the Fundão tailings dam investigation

- **“the failure of the Fundão tailings dam by liquefaction flowsliding was the consequence of a chain of events and conditions**
- **a change in design brought about an increase in saturation which introduced the potential for liquefaction**
- **soft slimes encroached into unintended areas on the left abutment of the dam**
- **this initiated a mechanism of extrusion of the slimes and pulling apart of the sands as the embankment height increased**
- **with only a small additional increment of loading produced by the earthquakes, the triggering of liquefaction was accelerated and the flow slide initiated”**

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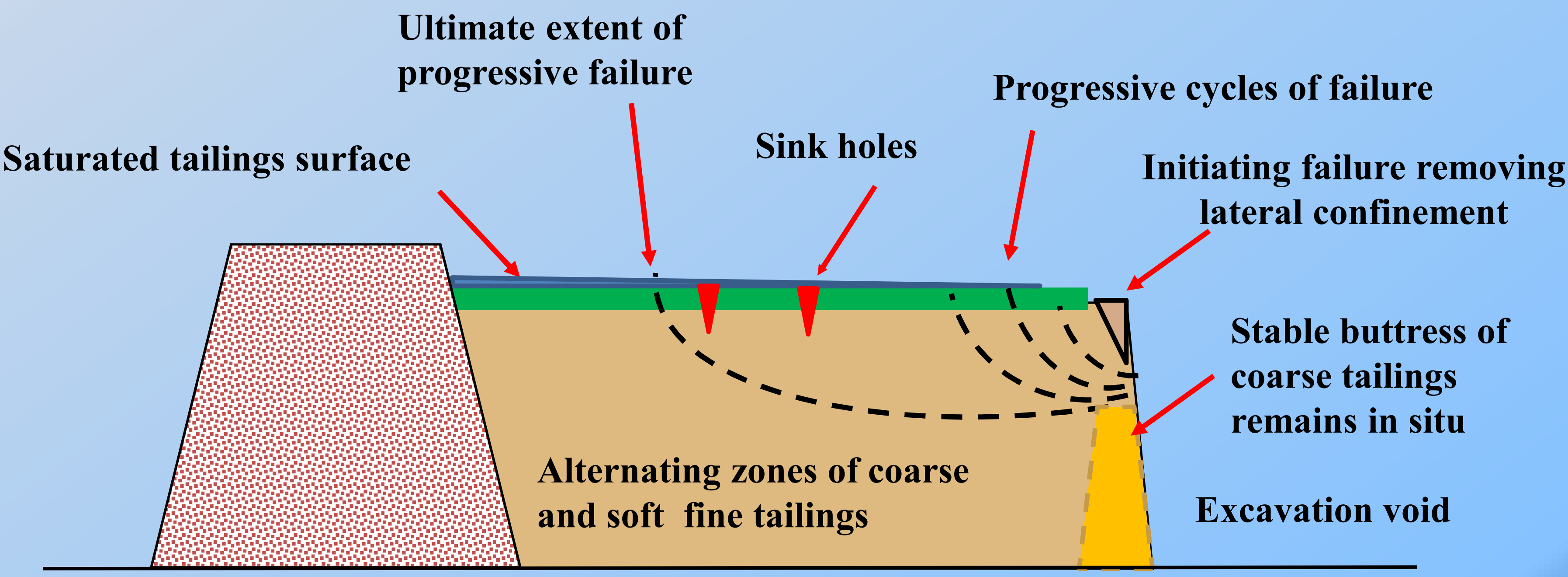
Parallel failures - Cavendish Mill TD1, UK in 2007

- The removal of lateral confinement via a small localised slope failure precipitated a series of liquefaction/flow slide events.
- Each failure induced further liquefaction events as the flow slide developed.
- 25,000m^3 were mobilised through the 3m wide initiating slope failure.



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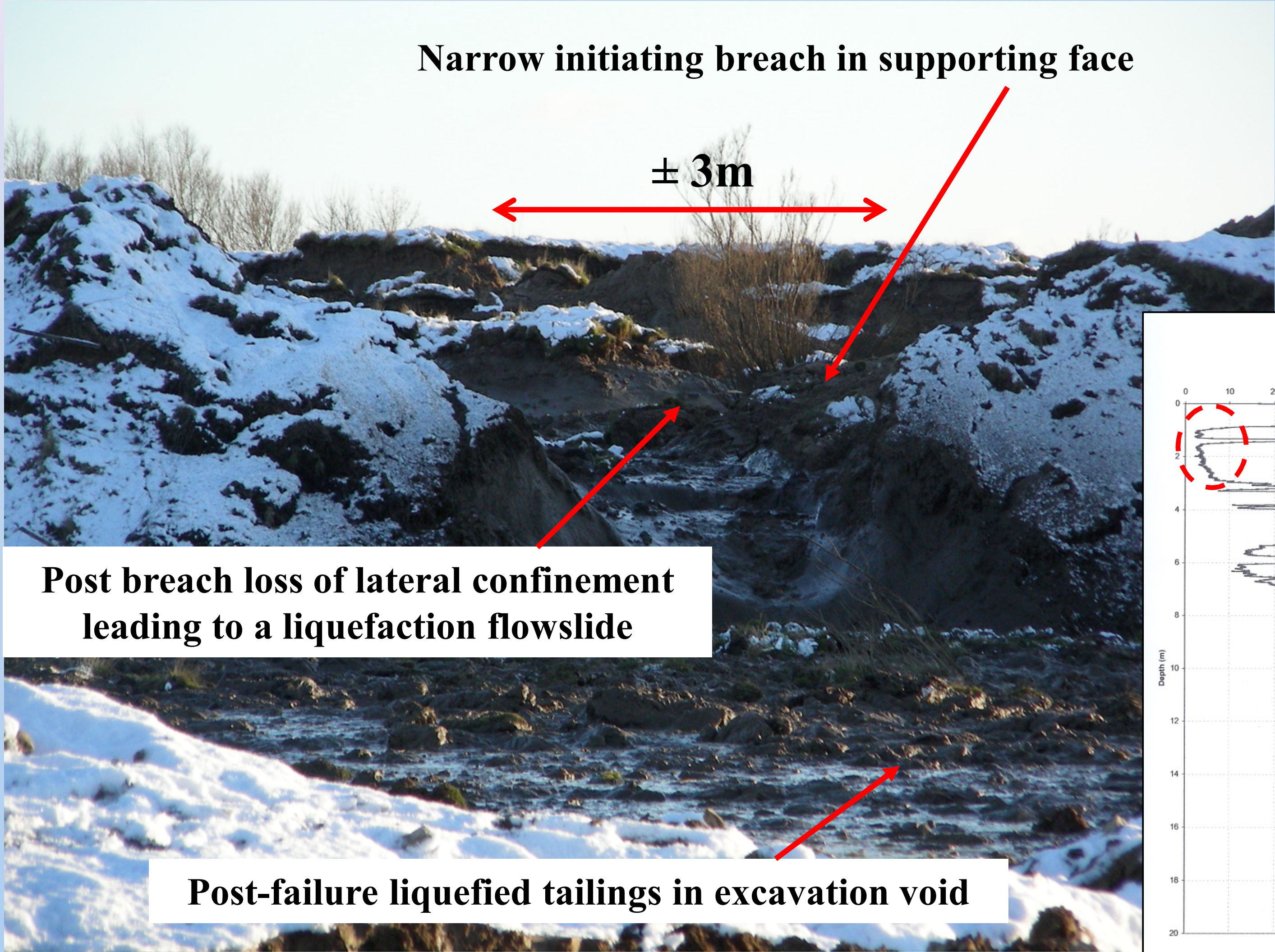
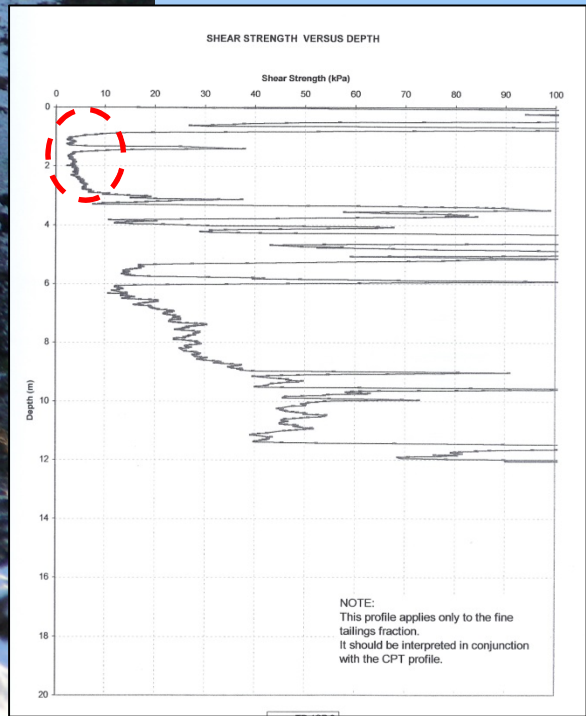
Parallel failures - Cavendish Mill TD1 in 2007





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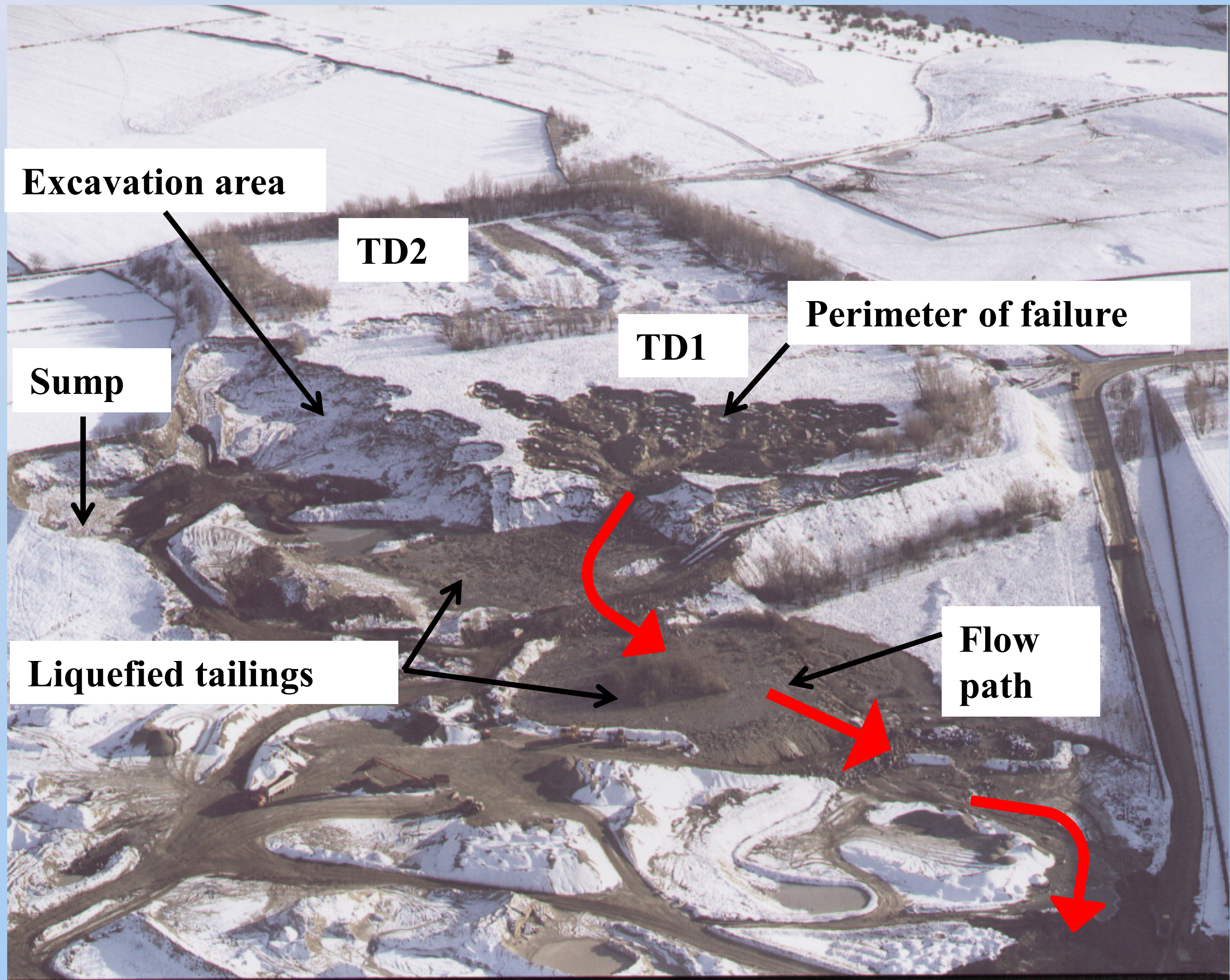
Parallel failures - Cavendish Mill TD1 in 2007



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Summary of the liquefaction events at Fundão and Cavendish Mill

In the case of both Samarco do Fundão and Cavendish Mill, post-failure analyses led to the conclusion that the failures were caused initially by:

- removal of lateral constraint
- subsequent rapid reduction in confining stress
- collapse and subsequent liquefaction of the tailings mass
- progressive failure as each slide triggered further liquefaction events
- the development of a flowslide into the downstream catchment

The extent of damage was enhanced by the presence of water bodies which aided the flow mechanisms.

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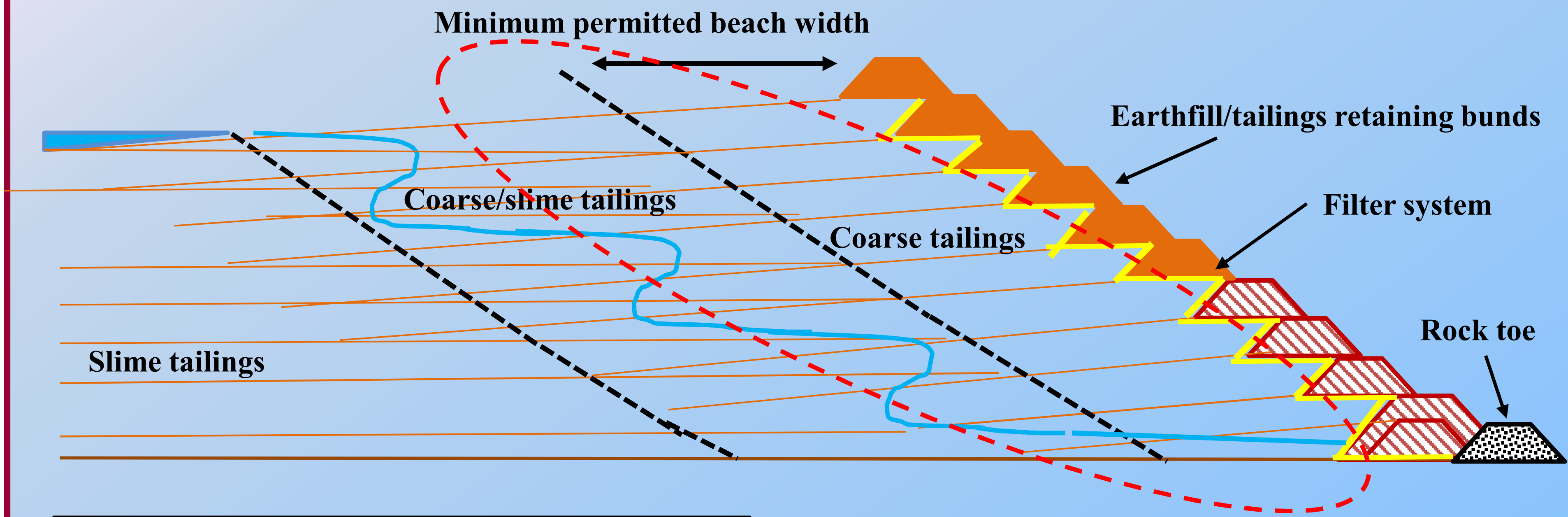
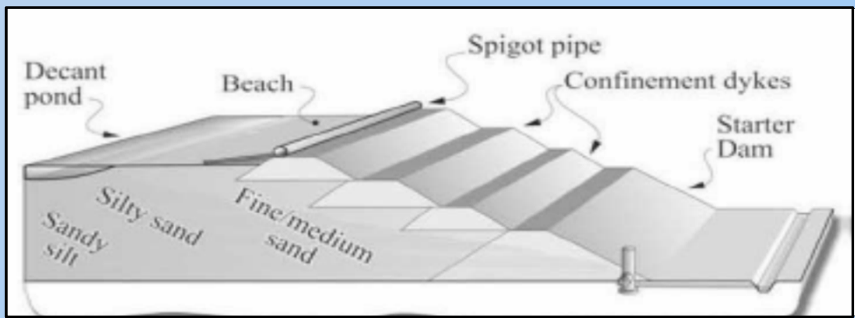
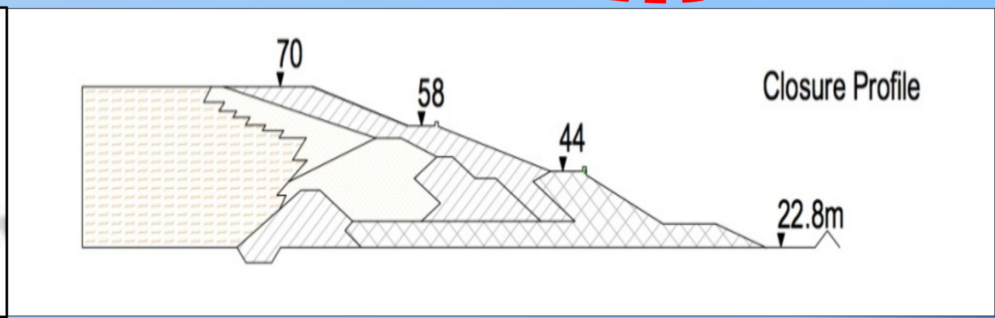
Darren Shaw, Arup
Rafael Monroy, Wood

Brumadinho Barragem No.1 - optimum design section





Zelazny Most, Poland



Clemows Valley Tailings Dam, UK

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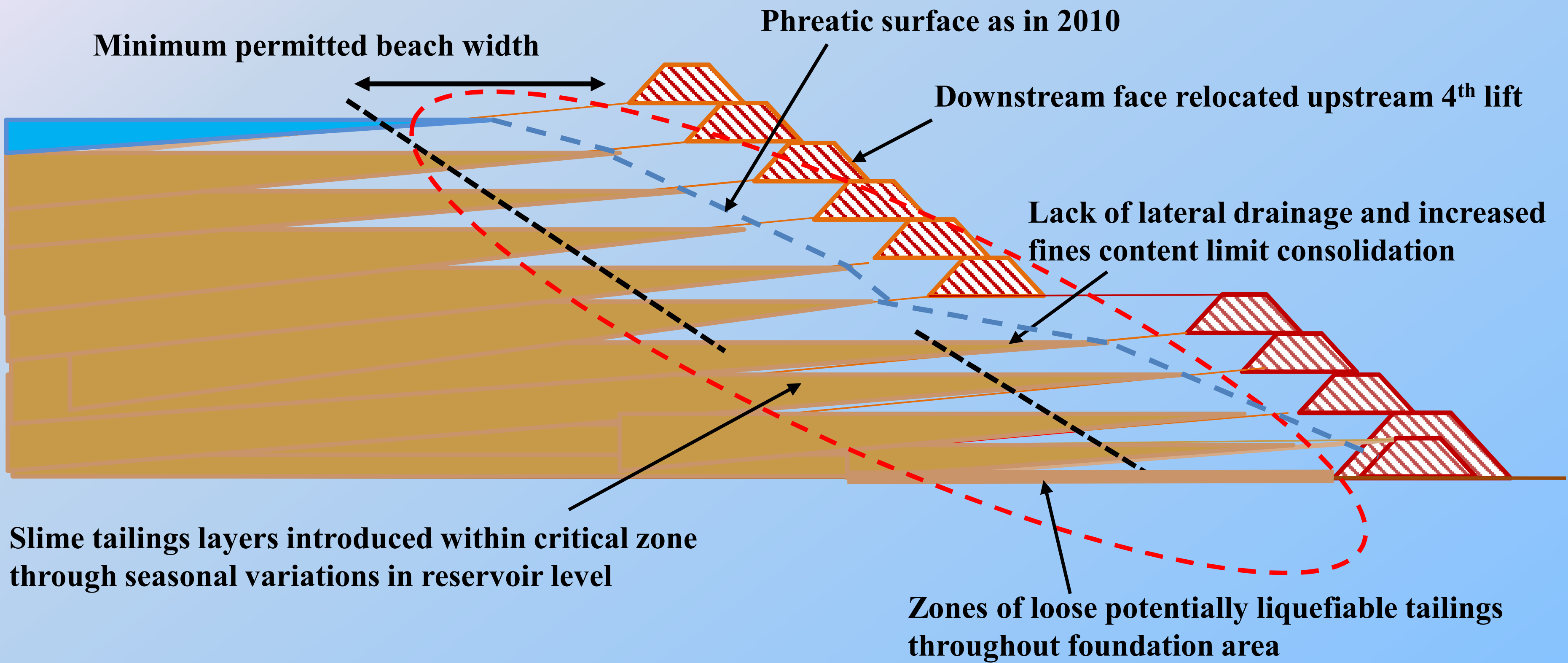
Darren Shaw, Arup
Rafael Monroy, Wood

Brumadinho Barragem No.1 - modified deposition system



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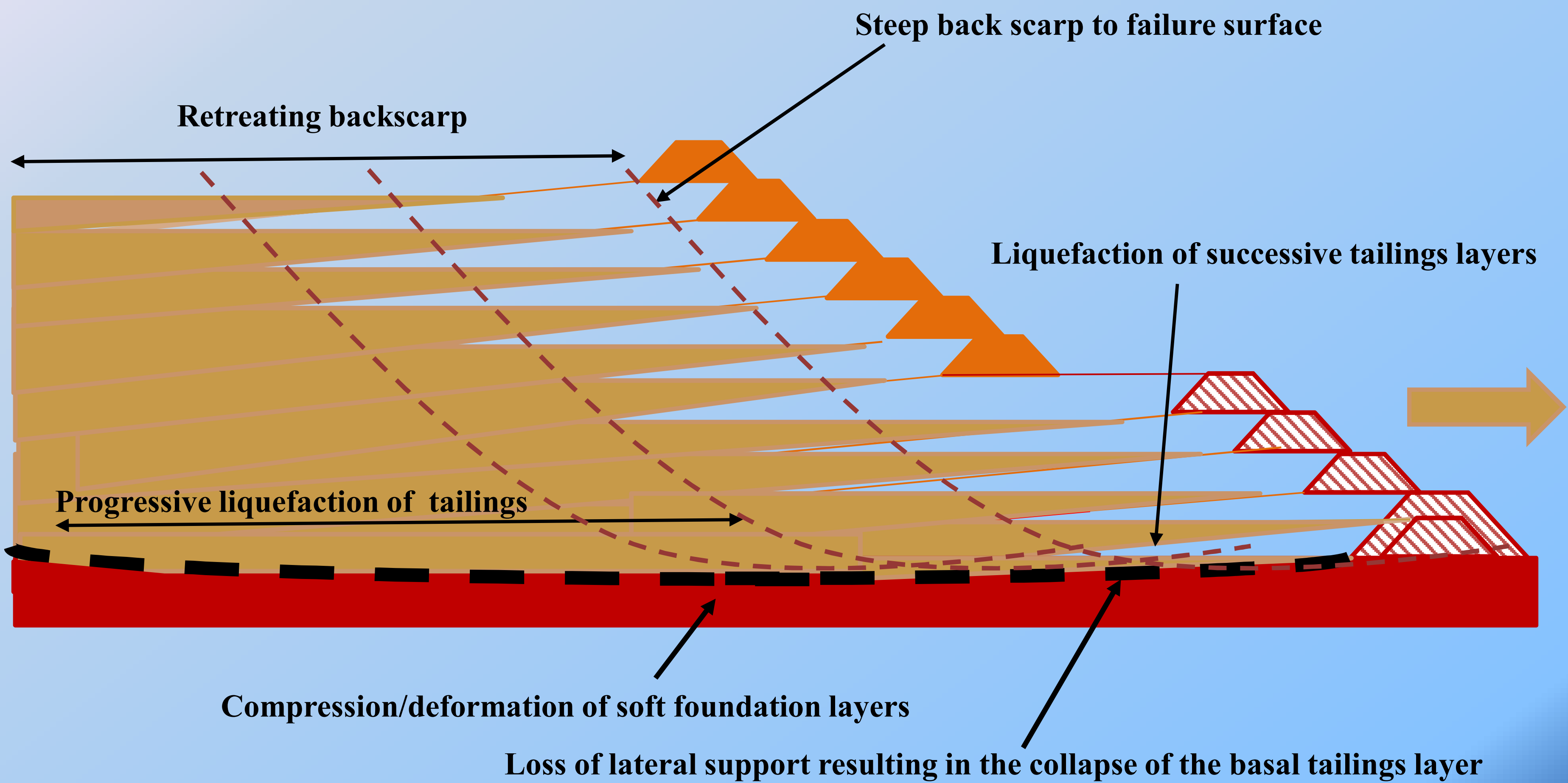
Preliminary assessment of the progressive failure of Brumadinho Barragem No.1



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Darren Shaw, Arup
Rafael Monroy, Wood

Summary of the failure of Brumadinho Barragem No.1 on 25th January 2019

At this stage it is premature to speculate on the cause, but publically-available information indicates that:

- **The lack of compliance with the original design/operating criteria would have led to the introduction of slime tailings into the embankment foundations.**
- **The grading of the tailings within the embankment foundation zone and the high sensitivity of this material to moisture changes would have exacerbated the potential for rapid strength loss and for liquefaction.**
- **The poor consolidation of the basal materials will have resulted in part from a lack of formal drainage provision.**
- **The appearance of seepage on the downstream face after lift four led to modification of the section.**
- **No seismic trigger mechanism has been reported for this site.**
- **The increased load on the foundation zone appears to have led to the collapse of the low density tailings underlying the confining wall, leading to liquefaction.**
- **Liquefaction of the embankment toe was followed by the rapid development of a series of complex arcuate failures from crest level.**
- **The liquefaction flow slide moved rapidly downstream, overwhelming both mine and other infrastructure, killing more than 242 people and severely degrading the environment for several hundreds of kilometres.**

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Summary of the aftermath of the failure of Brumadinho Barragem No.1 in 2019

The aftermath

- Brazilian police arrested two engineers and three Vale workers accused of having allegedly fraudulently vouched for the sturdiness of the dam which ruptured in Brumadinho.
- The clean up and recovery operation commenced immediately but it took more than six months to recover most of the bodies.
- The analyses carried out by Vale concluded that the tailings were not hazardous according to the standard since the toxicity indices are below the legal limits for mining tailings.
- Water quality testing of the Rio Paraopeba since the end of March detected no levels of mercury and lead above legal limits, though the state has prohibited direct water collection from the river as a preventative measure.
- The sediment plume did not reach the São Francisco River, remaining in the reservoir of the Baixo Retiro Plant in Pompéu, just over 300km downstream.

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Summary of the aftermath of the failure of Brumadinho Barragem No.1 in 2019

Activity since the January 25th 2019 incident

- **Vale's operational licence at the Brucutu mine has been suspended, reportedly for dam safety reasons, and production in the Paraopeba mining area has halted.**
- **In May 2019 the population immediately downstream of a further tailings dam in Minas Gerais also owned by Vale (the Gongo Soco facility) were evacuated due to the very high risk of failure of this facility.**
- **In order to protect communities, reduce the impact on the environment and to retain tailings from dams in an extreme breach scenario, Vale is carrying out three impoundment projects in areas downstream of the following dams:**
  - **a) 30m high 190m-long rockfill dam B3/B4 dams at Macacos**
  - **b) 36m high, 306m-long concrete dam at Barão de Cocais**
  - **c) 60m high 350m-long dam at Forquilha I**
- **The construction work is expected to be complete by early 2020 at a cost of some R$7.1 billion, and includes the de-characterisation of nine dams.**
- **An investigation team, which now includes international experts, has been established and was originally scheduled to report in October 2019. However, a six-month extension has been requested.**

Mike Cambridge, Cantab Consulting Ltd
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Rafael Monroy, Wood

Summary of the aftermath of the failure of Brumadinho Barragem No.1 in 2019

Regulatory changes

- As of February 11th 2019 a legally-binding obligation of daily inspections, with compulsory reporting of the findings, was introduced for dams constructed by the upstream method.
- Future construction of tailings dams using the upstream method has now been proscribed in Minas Gerais.
- All companies operating such facilities must present proposals for complete decommissioning within two-to-three years.
- The Minas Gerais State Civil Court has ordered Vale to refrain from depositing tailings into eight dams in the south-eastern area of its operations. However, of the affected dams, three built using the upstream method were already out of commission.
- A number of dams with current Stability Condition Statements have been shut down to comply with a request from Brazil's National Mining Agency.
- The resourcing of ANM to effect appropriate oversight of the inspection and reporting regime does not appear to have been explicitly addressed.

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Summary of the aftermath of the failure of Brumadinho Barragem No.1 in 2019

- **Brumadinho Barragem No 1 was owned and operated by Vale, one of the largest mining companies in the world, which also jointly owned the Samarco de Fundão dam.**
- **The confining embankment and deposition strategy at Brumadinho is reported not to have conformed to the original design specification being modified to suit operational issues.**
- **The Owner has indicated that the piezometers gave no indication of imminent collapse.**
- **Leakage was reported after lift 4 and in subsequent phases with the development of toe seepage a few months prior to the dam burst.**
- **The dam is reported to have been declared safe by an independent inspecting body in 2018.**
- **On-site inspections took place in December 2018 and January 2019 with no untoward concerns reported.**
- **The failure appears to have occurred through liquefaction of the underlying tailings layers, resulting in a flowslide which led to more than 240 deaths.**
- **Further environmental damage was limited by the presence of the Baixo Retiro reservoir 300km downstream.**
- **The precautions taken at Gongo Soco in May 2019 suggest that other similar structures may only be quasi-stable.**

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Post-Brumadinho global initiatives

"International standard for tailings storage facilities"

This is one of the outputs of the global tailings review (GTR) team, co-convened by the International Council on Mining and Metals (ICMM), the United Nations Environment Programme (UNEP) and the Principles for Responsible Investment (PRI) and will include

- **Consequence-based classification system**
- **System of credible, independent review**
- **Requirements for emergency planning and preparedness for each classification level**

ICMM "Guidance on tailings management"

Document developed by ICMM's tailings Working Group to provide guidance on principles and practices for tailings management

ICOLD "Guidelines for tailings dam safety assessment and design"

This Bulletin focuses on technical aspects so that it can support the intended Global Standard being prepared by ICMM/Investor Group/UNE and other industry bodies.

prEN 16907-7 Earthworks — Part 7: Hydraulic placement of extractive waste

This European Standard is being based on *"The Hydraulic Transport and Storage of Extractive Waste, Guidelines to European Practice", Springer Books 2018*

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Comparison of the liquefaction events at Brumadinho with those at Samarco do Fundão and Cavendish Mill

In the case of both Samarco do Fundão and Cavendish Mill, post-failure analyses led to the conclusion that the failures were caused initially by:

- **removal of lateral constraint - in the case of Fundão by deformation of the basal tailings**
- **subsequent rapid reduction in confining stress**
- **collapse and subsequent liquefaction of the tailings mass**
- **progressive failure as each slide triggered further liquefaction events**
- **the development of a flowslide into the downstream catchment**

The extent of damage was enhanced by the presence of water bodies which aided the flow mechanisms.

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Conclusions re upstream construction

"…However, I side with the views of Martin & McRoberts (1999) and others before them (e.g. Lenhart, 1950; Vick, 1992) that …

- **there is nothing wrong with upstream tailings dams provided that key principles are adhered to in the design, construction, and operation of such dams.**
- **…for purposes of preliminary design that liquefiable deposits that can liquefy be assumed to do so and that containment be provided by a buttress of non-liquefiable unsaturated tailings and/or compacted dilatant material.**
- **…it is essential to continually demonstrate by monitoring that the assumed unsaturated conditions in the buttress persist if relied upon in the design and that the buttress is behaving as intended."**

Morgenstern (2018)

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood

Conclusions re upstream construction

In summary, upstream construction:

- **is not inherently unstable;**
- **has less flexibility to accommodate ongoing design or operational changes;**
- **requires greater management input throughout its life;**
- **requires a significantly greater hydrological and geotechnical input;**
- **is likely to be more vulnerable to seismic disturbance.**

Best practice recognises that, where a commitment to greater management of design and day-to-day operation is not feasible, upstream construction methods should be avoided.

Thank you for your attention

Mike Cambridge, Cantab Consulting Ltd
Darren Shaw, Arup
Rafael Monroy, Wood