Challenges and Advances in Mining Waste Management in Brazil

Japanese Geotechnical Society (May 2024)

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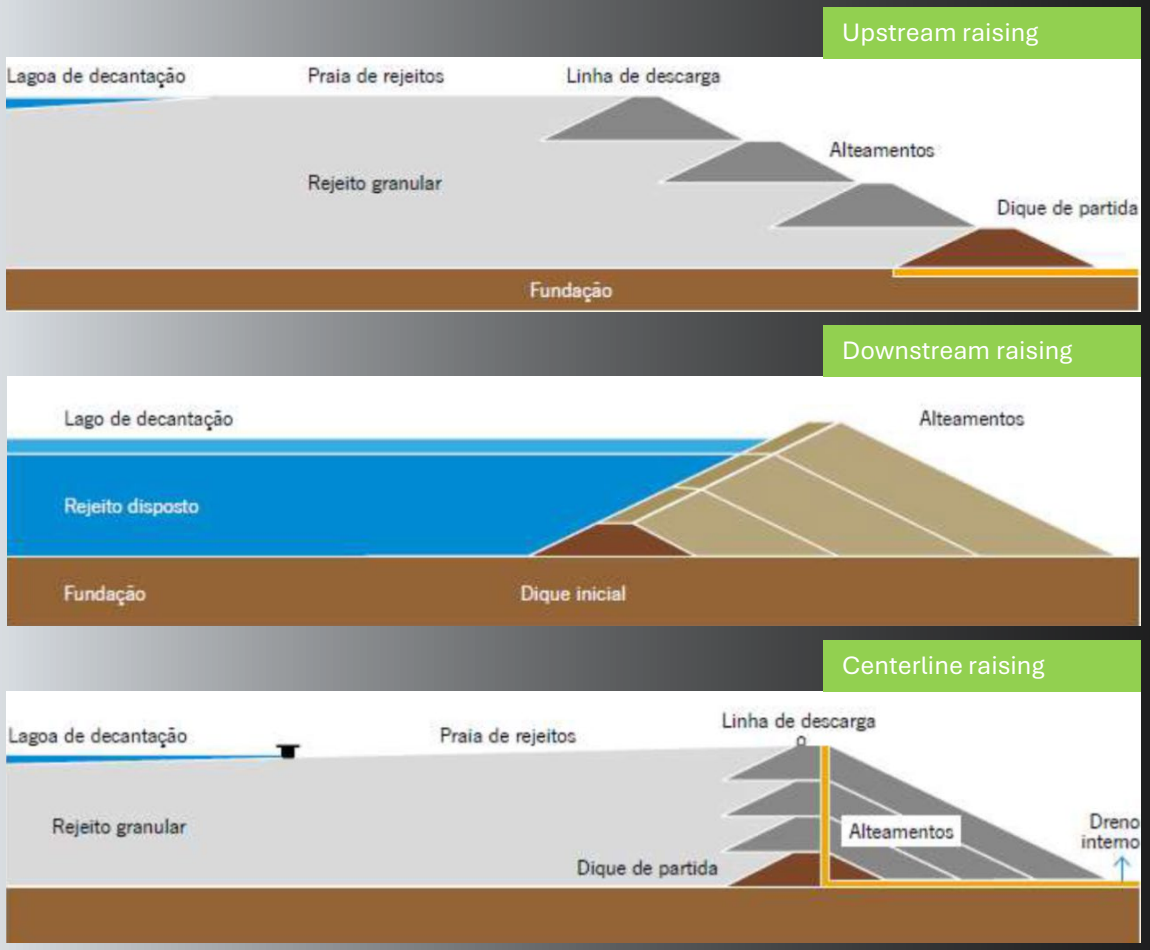
Summary



SOURCE: IBRAM (2016)

In Brazil, dams are the most common way of disposing of wet tailings on the surface through direct release

- Utilization of the tailings themselves as construction material.
- Multiple raisings diluting investments over time.

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- Brazil has 890 mining waste containment dams

Total number of Dams: 890

Total number of Dams with APD – High: 268

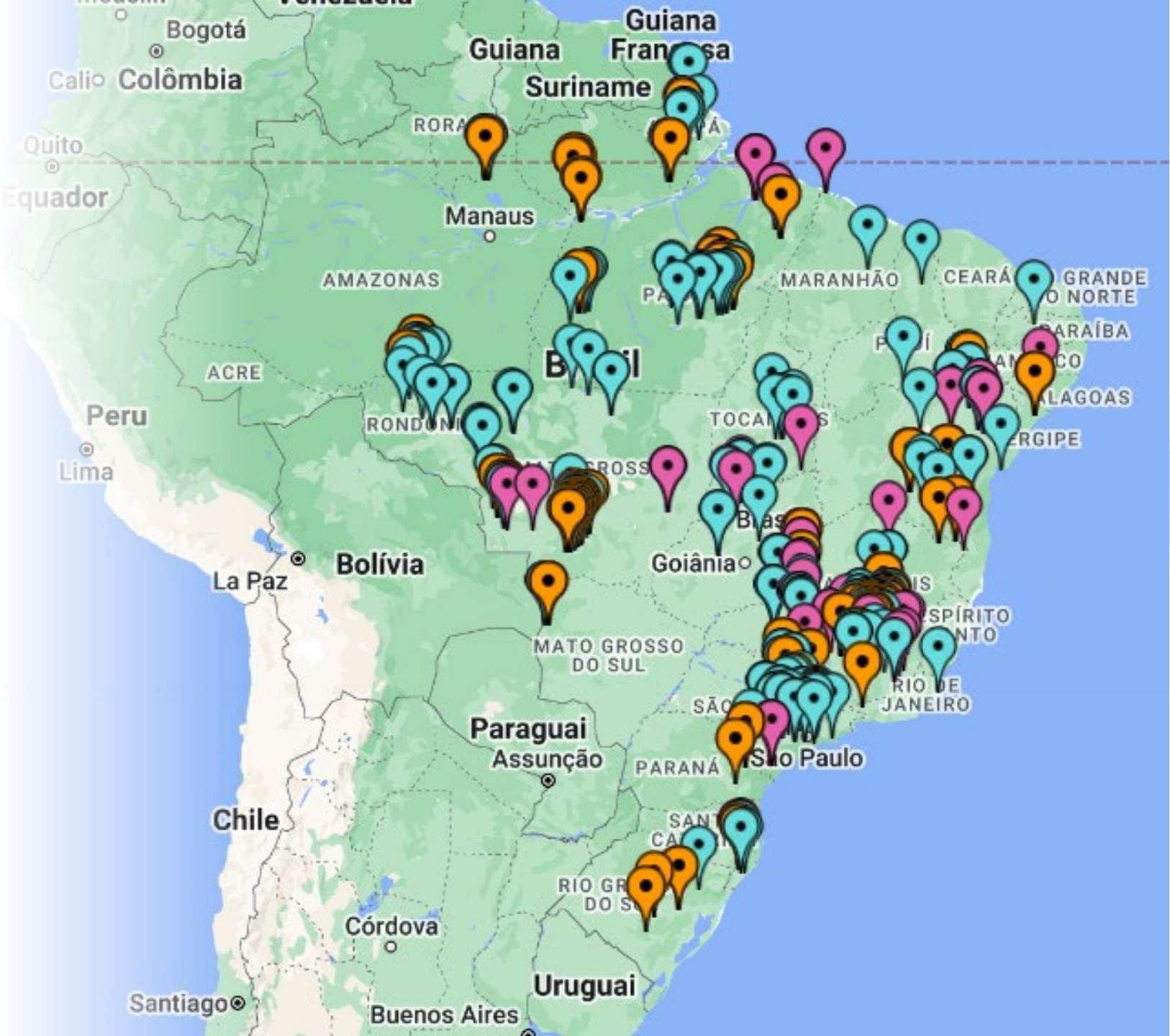
Total number of Dams with APD – Medium: 156

Total number of Dams with APD – Low: 466

LEGENDA:

- Associated Potential Damage – High
- Associated Potential Damage – Medium
- Associated Potential Damage – Low

SOURCE: ANM (anm.gov.br)



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Economic and Social Importance of Mining in Brazil:

- Revenue in 2023 was R$248 billion
- 210,000 direct jobs in the sector
- Export of 392 million tons of mineral products totaling US$43 billion
- Iron ore represents 71% of the export value
- Trade balance surplus accounts for 32% of the country's total at US$31.95 billion
- Minas Gerais - 46.4% of the country's revenue

SOURCE: IBRAM (ibram.org.br/publicacoes)

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- Minas Gerais

  Area = 586.528 km^2

Total number of Dams: 339

Total number of Dams with APD – Alto: 153

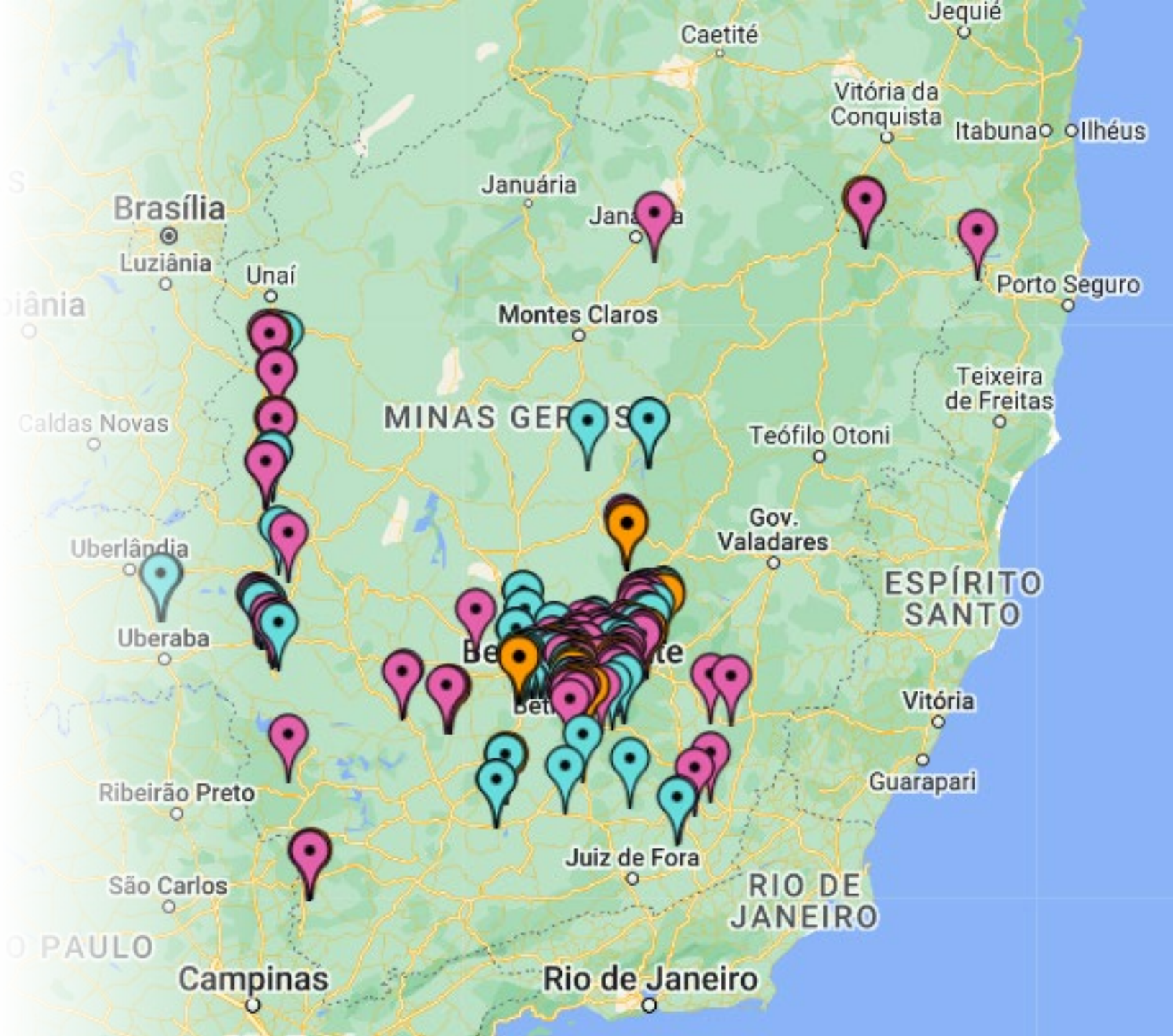
Total number of Dams with APD – Médio: 34

Total number of Dams with APD – Baixo: 152

LEGENDA:

- Associated Potential Damage – High
- Associated Potential Damage – Medium
- Associated Potential Damage – Low

SOURCE: ANM (anm.gov.br)



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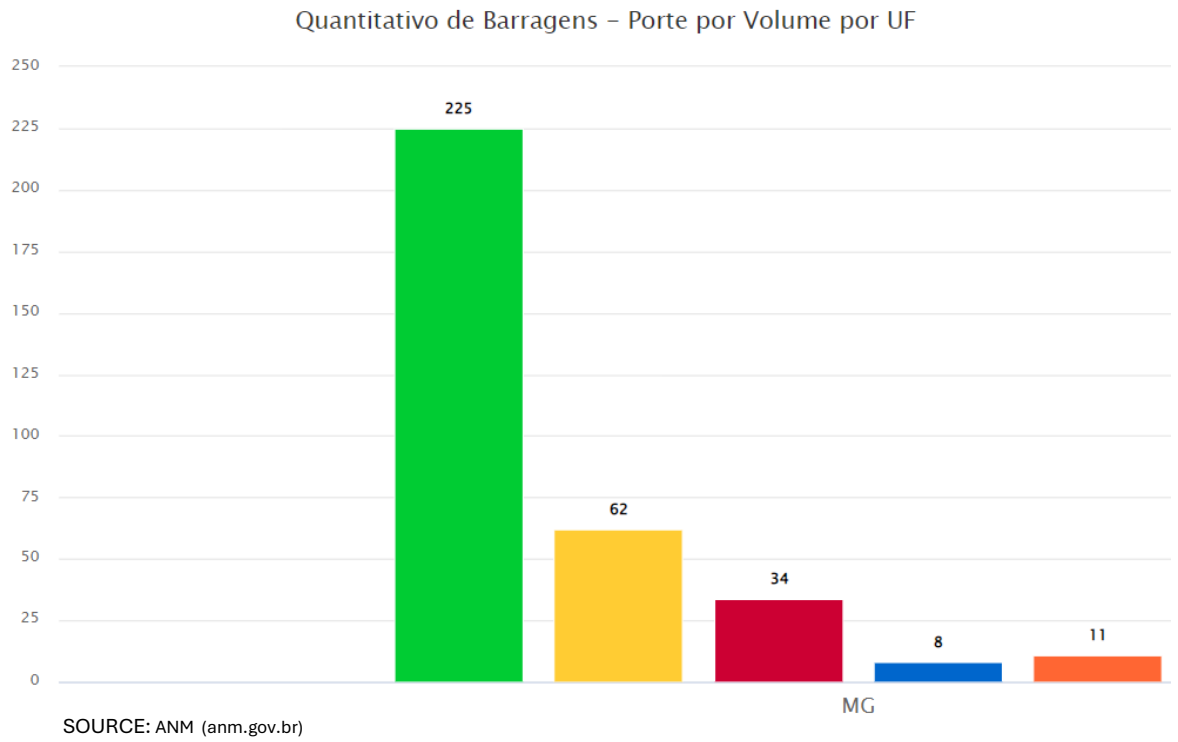
- Very Small ≤ 500 thousand m^3
- Small 500 thousand to 5 million m^3
- Medium 5 million to 25 million m^3
- Large 25 million to 50 million m^3
- Very Large ≥ 50 million m^3



SOURCE: ANM (anm.gov.br)

MG Overview

- For the 11 dams with a volume > 50 million m^3 of MG
  - 6 are Iron Ore / 2 Primary Gold Ore / 2 Phosphate / 1 Itabirite
  - Height between 57 and 163m
  - 5 Downstream Raising / 4 Centerline Raising / 2 Upstream Raising
  - 2 dams at Emergency Level 1 without a certificate of stability

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Dam Name	Entrepreneur Name	Municipality	Main Ore	Current Height(m)	Current Volume(m^3)	Construction Method	Risk Category	Associated Potential Harm	Emergency Level	Status DCE RPSB
South (Canal Stream)	VALE S.A.	SÃO GONÇALO DO RIO ABAIXO	Iron Ore	83	58.841.522,26	2 - Downstream raising	Low	High	No Emergency	Certificate
Casa de Pedra Dam	CSN MINERACAO S.A.	CONGONHAS	Iron Ore	84	65.374.575,00	2 - Downstream raising	Low	High	No Emergency	Certificate
Maravilhas II	VALE S.A.	ITABIRITO	Iron Ore	86,72	86.115.233,76	2 - Downstream raising	Low	High	Emergency Level 1	Não Atestado
BR Dam	MOSAIC FERTILIZANTES P&K LTDA.	TAPIRA	Phosphate	57	88.056.149,00	5 - Centerline raising	Low	High	No Emergency	Certificate
Germano Dam	SAMARCO MINERACAO S.A. EM RECUPERACAO JUDICIAL	MARIANA	Itabirite	163	129.590.000,00	10 - Upstream raising	Low	High	No Emergency	Certificate
Tailings Dam	ANGLO AMERICAN MINERIO DE FERRO BRASIL S/A	CONCEIÇÃO DO MATO DENTRO	Iron Ore	60	147.780.000,00	2 - Downstream raising	Low	High	No Emergency	Certificate
Itabiruçu	VALE S.A.	ITABIRA	Iron Ore	71,96	172.719.161,20	2 - Downstream raising	Low	High	No Emergency	Certificate
BL-1 Dam	MOSAIC FERTILIZANTES P&K LTDA.	TAPIRA	Phosphate	98	196.945.389,00	5 - Centerline raising	Low	High	No Emergency	Certificate
Pontal	VALE S.A.	ITABIRA	Iron Ore	68	218.964.640,00	10 - Upstream raising	Low	High	Emergency Level 1	Não Atestado
Santo Antônio Dam	KINROSS BRASIL MINERACAO S/A	PARACATU	Primary Gold Ore	104	361.312.440,00	5 - Centerline Raising	Low	High	No Emergency	Certificate
Eustáquio Dam	KINROSS BRASIL MINERACAO S/A	PARACATU	Primary Gold Ore	106	440.642.566,00	5 - Centerline raising	Low	High	No Emergency	Certificate

SOURCE: ANM (anm.gov.br)

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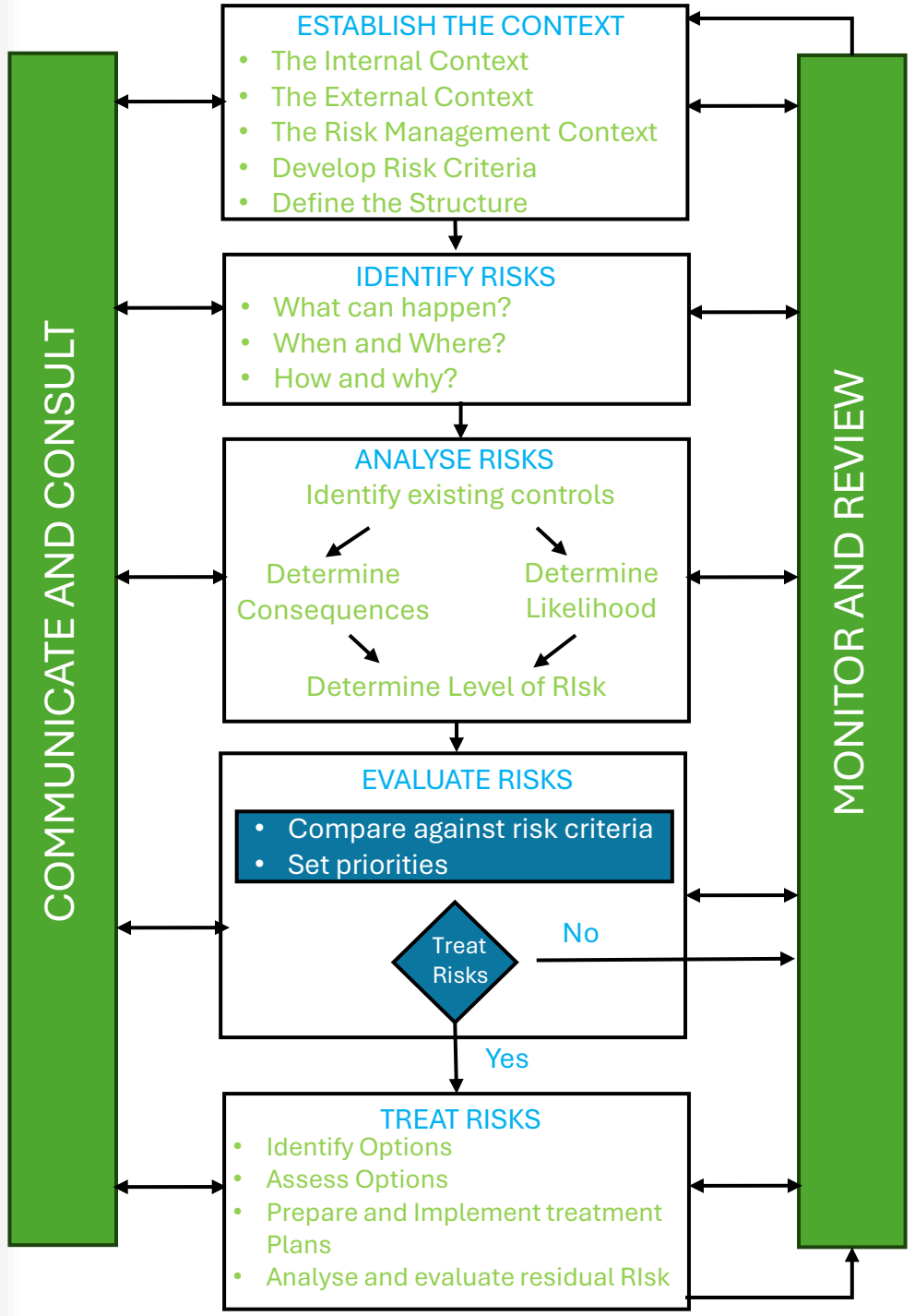
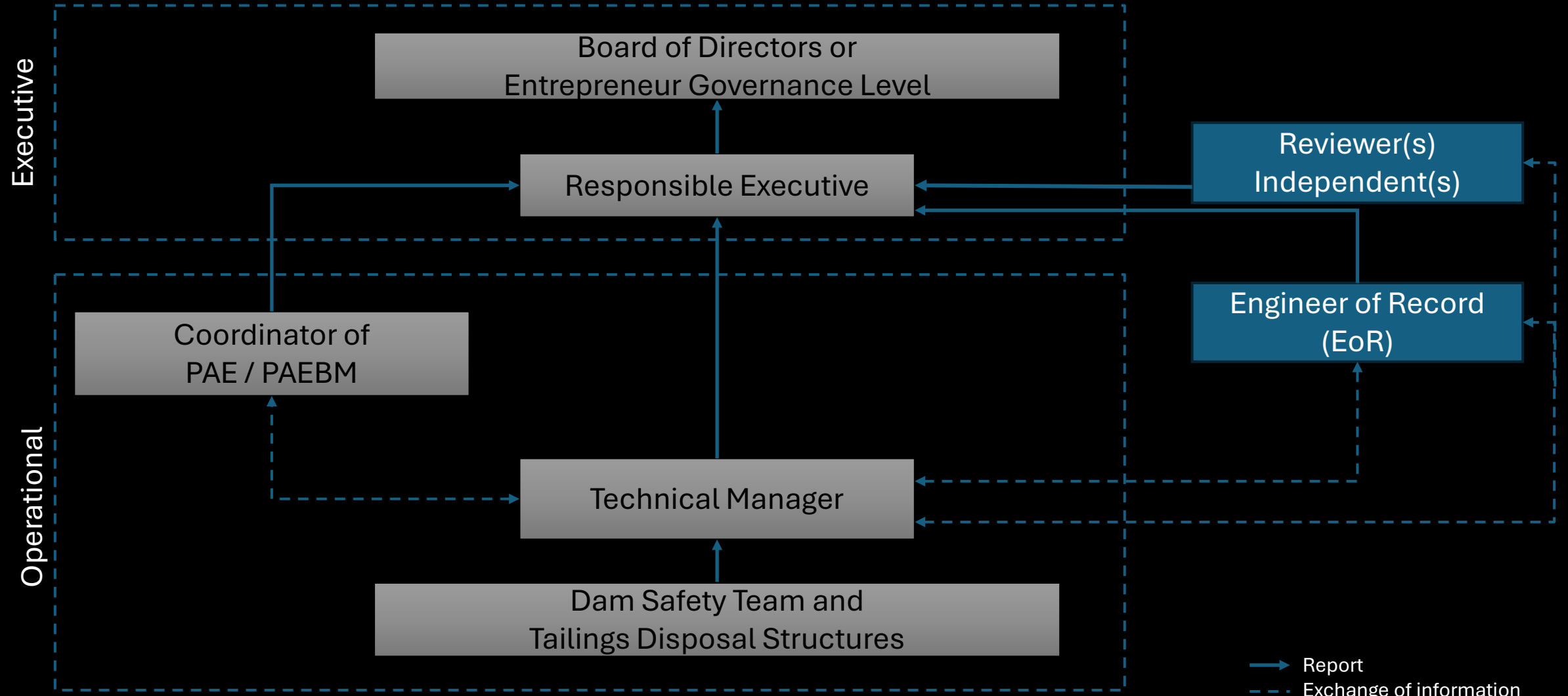
Geotechnical Risks

- Establish the Context
- Identify the Risks
- Analyze the Risks
- Assessing the Risks
- Treating the Risks
- Monitoring and Review
  - Risks of breakage/leakage
  - Environmental and socio-economic impacts



SOURCE: Adaptado ISO31.000:2018

Reporting of information on the management of dam structures and tailings disposal



SOURCE: Good Practices Guide for Management of Dams and Tailings Disposal Structures

Integration of Operation, Monitoring, Maintenance and Risk Management processes in the Operation phase

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Operation (6.1)

- Definition of operational controls and critical controls (6.1.1)
- Operation Manual, Monitoring and Maintenance (6.1.2)
- **Operation Execution**
  - Sys.management Operational (6.1.3)
  - Management and Water Balance (6.1.5)
  - Control of disposed tailings (6.1.4)
  - Structure Raising (6.1.6)
- Characteristics of tailings disposal structures

Monitoring (6.2 e 6.3)

- Dams Mining (Appendix 1)
- Other Structures Tailings Disposal
- Classification of Dams
- PSB / PAEBM
- Records in SIGBM
- **Execution and Monitoring Geotechnical and Structural**
  - Visual Inspections (6.2.1)
  - Instrumentation and data collection (6.2.3)
  - Security Review (6.2.2)
  - Instrumentation Analysis (6.2.4)
- **Operationalization of the PAEBM (6.4)**
  - Internal Trainings
  - External Simulations
- Environmental monitoring (6.3)
- Anomaly Records

Maintenance (6.5)

- Maintenance planning
- Maintenance Procedures
- **Execução da Manutenção**
  - Systematic Preventive Maintenance
  - Non-systematic Preventive Maintenance
  - Corrective Maintenance
  - Improvement Works
- Maintenance Records

Risk Management (6.7.3)

- Risk Identification
- Risk Analysis
- Risk Assessment
- Primary Risks
- Secondary Risks
- Treatment of Risks
- Registration of Risks
- Monitoring and Change Control

SOURCE: Good Practices Guide for Management of Dams and Tailings Disposal Structures

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Accident Consequences

- Failures cost money, human lives, and environmental losses
- The direct costs of a dam incident can reach billions of dollars, typically ranging from tens of millions to billions.
- The overall costs to the organization and shareholders can often be much higher
- Tailings Dams are business risks that must be managed

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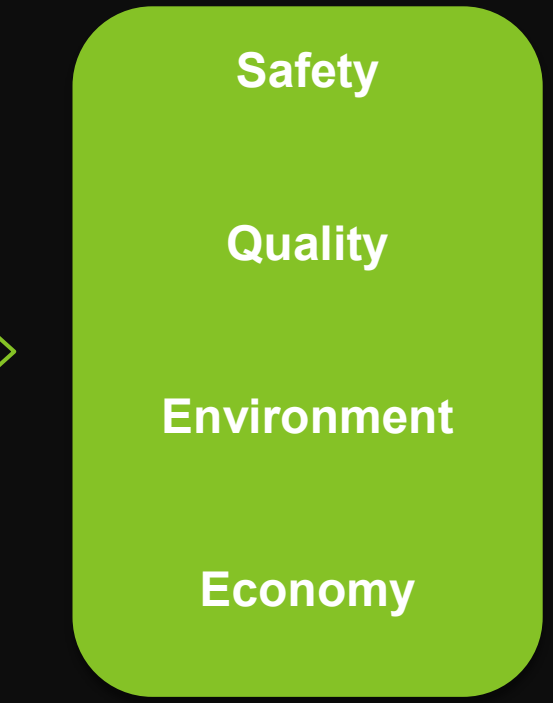
Risk management

- Dams Operation Manual
- Dam Risk Charts
- PAEBM
- External Audits
- Monitoring and Periodic Inspections



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Technologies and Innovations for Tailings Dams Management

- Technological advancements for monitoring and security
- Use of geotechnologies

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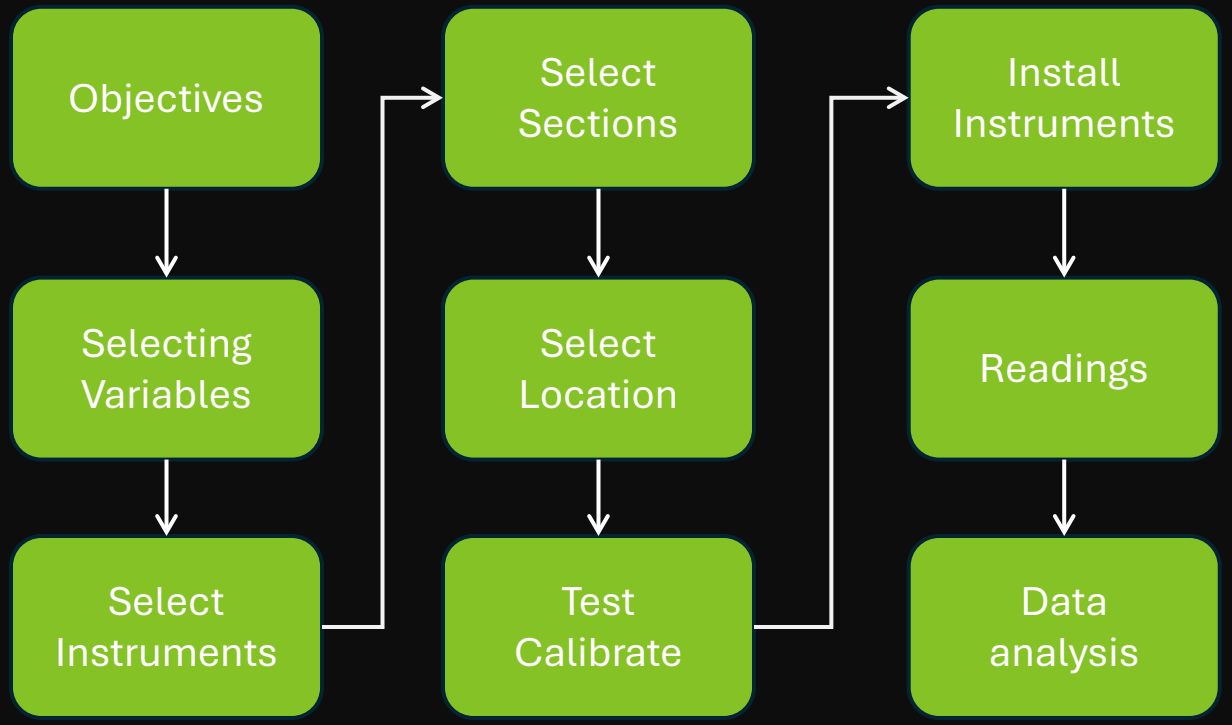
Monitoring

- Water level and piezometric;
- Reservoir water/tailings level;
- Flow Measurement;
- Precipitation Meters;
- Offsets;
- Settlements; and,
- Vibrations



SOURCE: Ortigão (2013)

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Doppler Radar

Technology

Description

- Able to identify very small movements and targets (e.g., 0.3 m x 0.3 m at 1 km).
- Emergency instrument.

Alert trigger

- Association rules are used to trigger alarms due to abrupt movement in the dam mass.

https://www.em.com.br/app/noticia/gerais/2019/04/08/interna_gerais,1044582/conheca-o-radar-que-vigia-barragem-com-risco-de-rompimento-em-macacos.shtml

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Tiltmeter

Technology

Description

- An instrument that measures inclination and acceleration.
- Emergency instrument.

Trigger of possible collapse

- 60% of sensors with a tilt greater than the limit.

Collapse trigger

- 100% of sensors with inclination greater than the limit.

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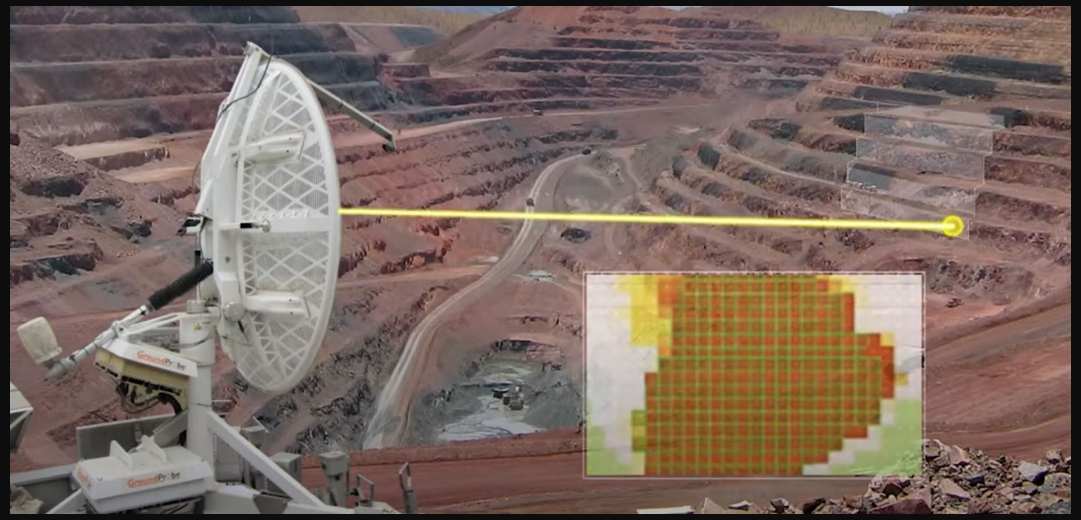
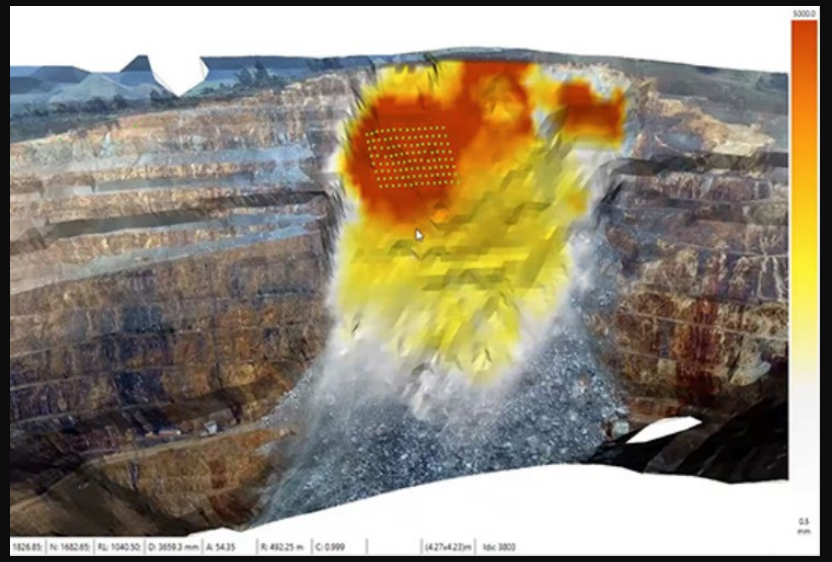
SSR-XT Radar

Technology



Operation

- It scans a specific region. Using a narrow beam generated by the radar, it's possible to reproduce a heat map on the 3D image of the region of interest.
- All data is reproduced in real-time to obtain accurate field information.



https://www.groundprobe.com/wp-content/uploads/2017/06/SSR-XT-Flyer-GroundProbe-Portuguese.pdf
https://www.youtube.com/watch?v=j0TRge6qfyE&t=20s

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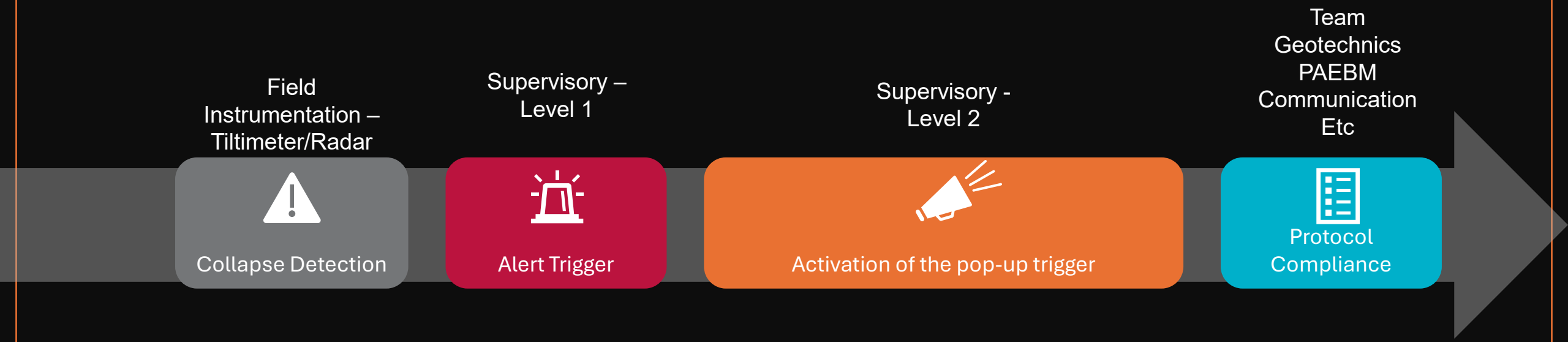
Macro Flow of Automatic Siren Triggering

The automatic activation of the sirens is done using tiltmeter/doppler radar sensors to detect the rupture and trigger the siren system.

More monitoring options result in redundancy of detection, increasing security.



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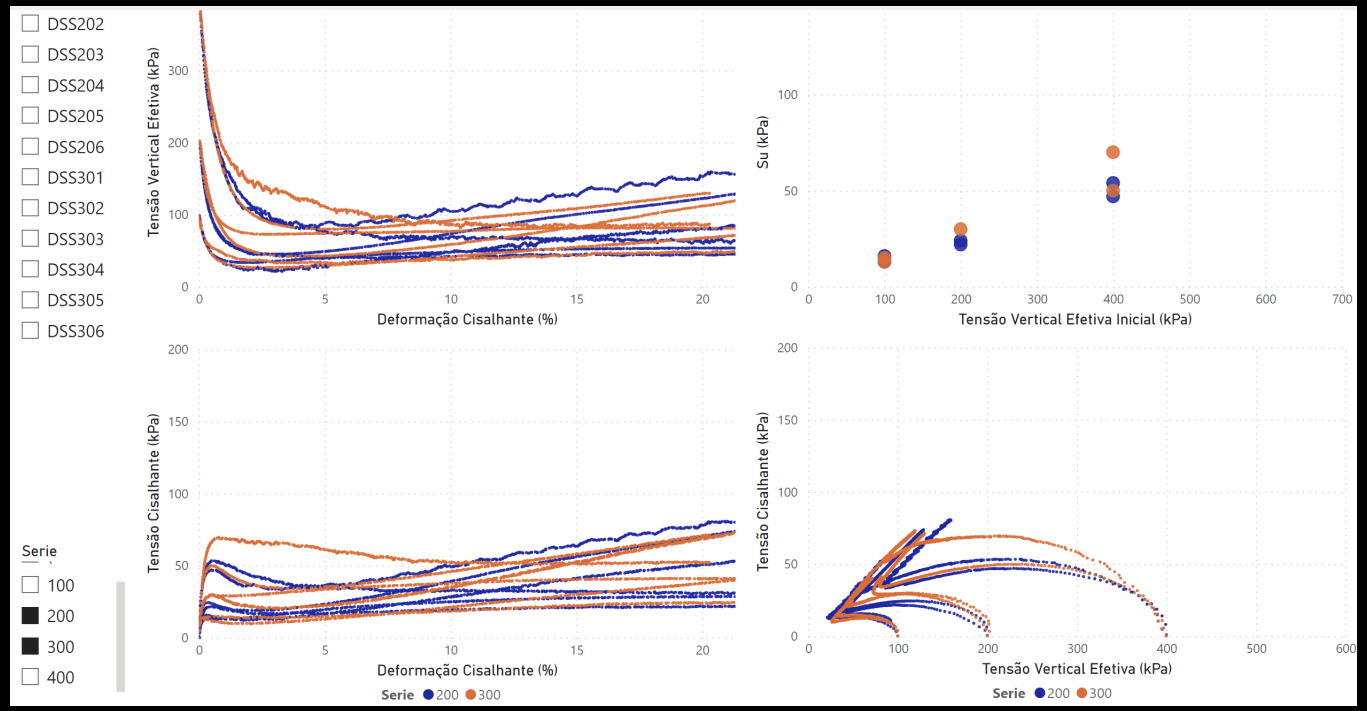
Geotechnical Tests

- Evaluate shear strength and slope stability of dam embankments.
- Analyze the deformability and consolidation potential of tailings during the dam's lifespan.
- Study the generation of neutral pressures and the risk of liquefaction.
- Investigate anisotropic behavior and susceptibility to progressive failure of tailings.

Special Dynamic Soil Tests (DSS)

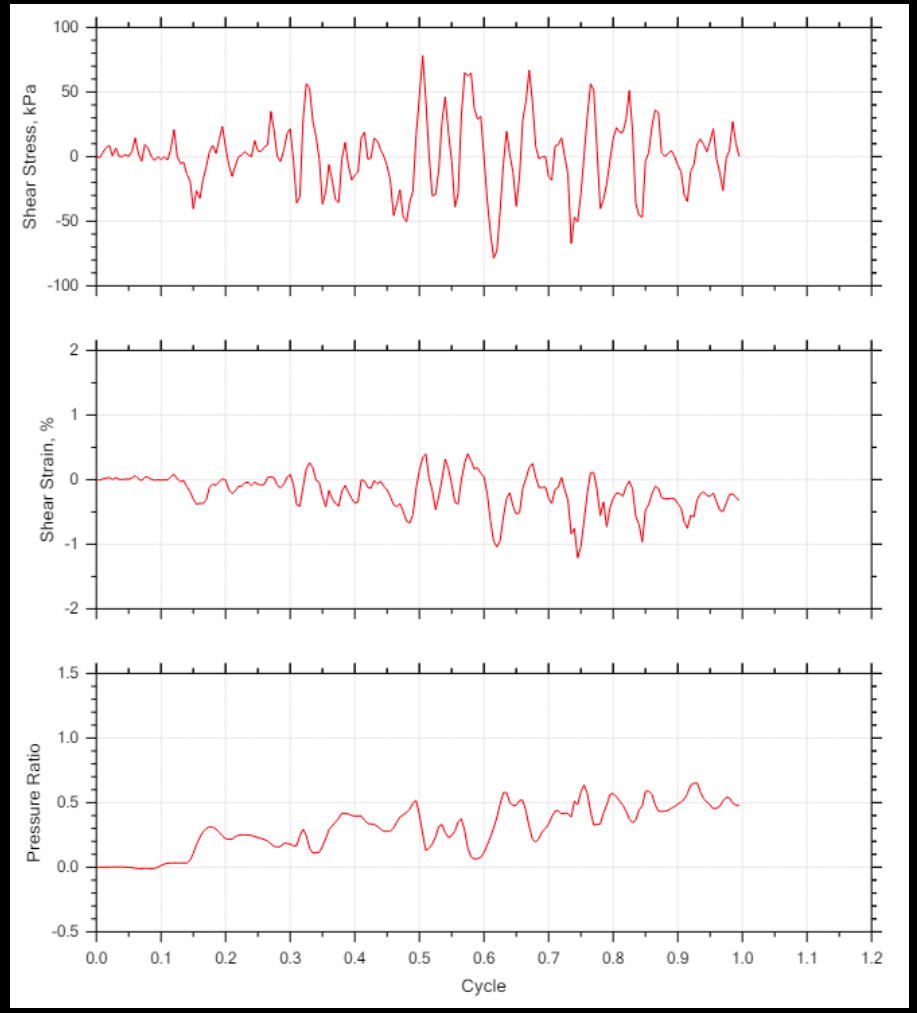
- "They assess the dynamic response of tailings under cyclic loads, such as earthquakes or vibrations induced by machinery.
- Useful for analyzing liquefaction, deformability, and fatigue resistance of tailings."



SOURCE: Geocompany files.

Cyclic Direct Simple Shear Test System with Simulated Drainage (CDSS)

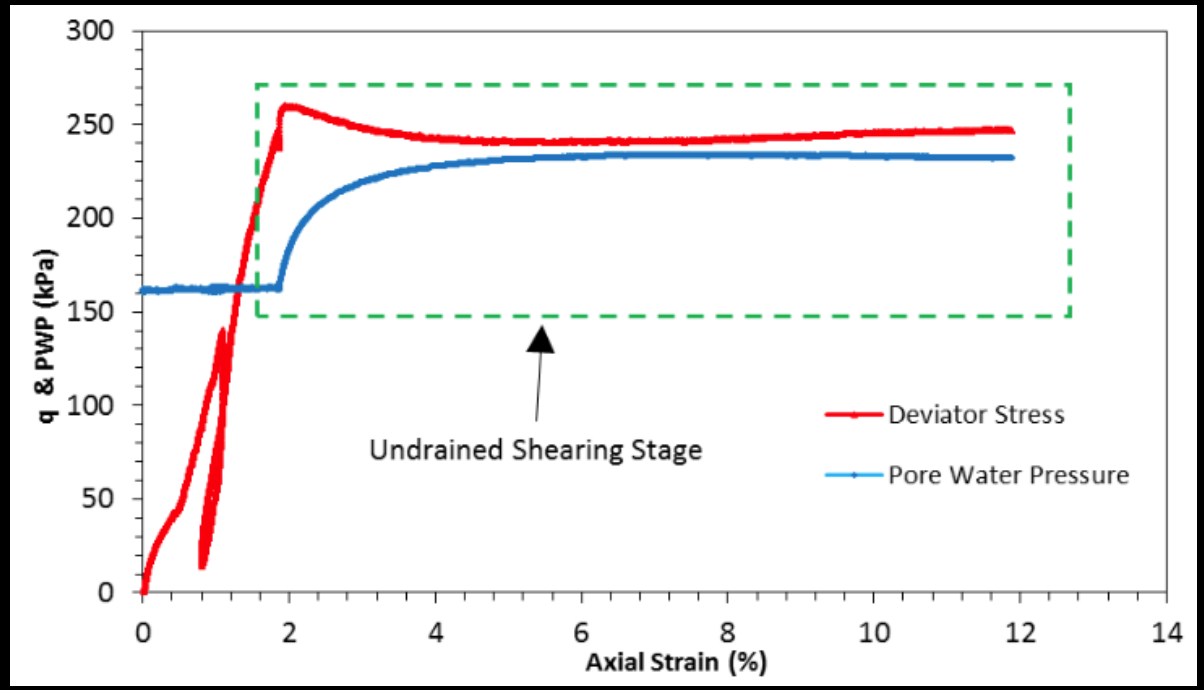
- They combine characteristics of triaxial and DSS tests, better simulating the real loading conditions in dams.
- They allow the evaluation of the expansion, densification and progressive rupture of tailings under cyclic loads and variable drainage.



https://www.geocomp.com/files/products/outputs/cyclic-direct-simple-shear-test-report.pdf - Geocomp Sample Geotechnical Report (CDSS)

Anisotropically Consolidated Undrained Compression Test (CAU)

- They allow controlled axial and radial deformations to be imposed on the sample, providing greater flexibility in the analysis of tailings behavior.
- Useful for studying the anisotropy and rotational behavior of tailings.



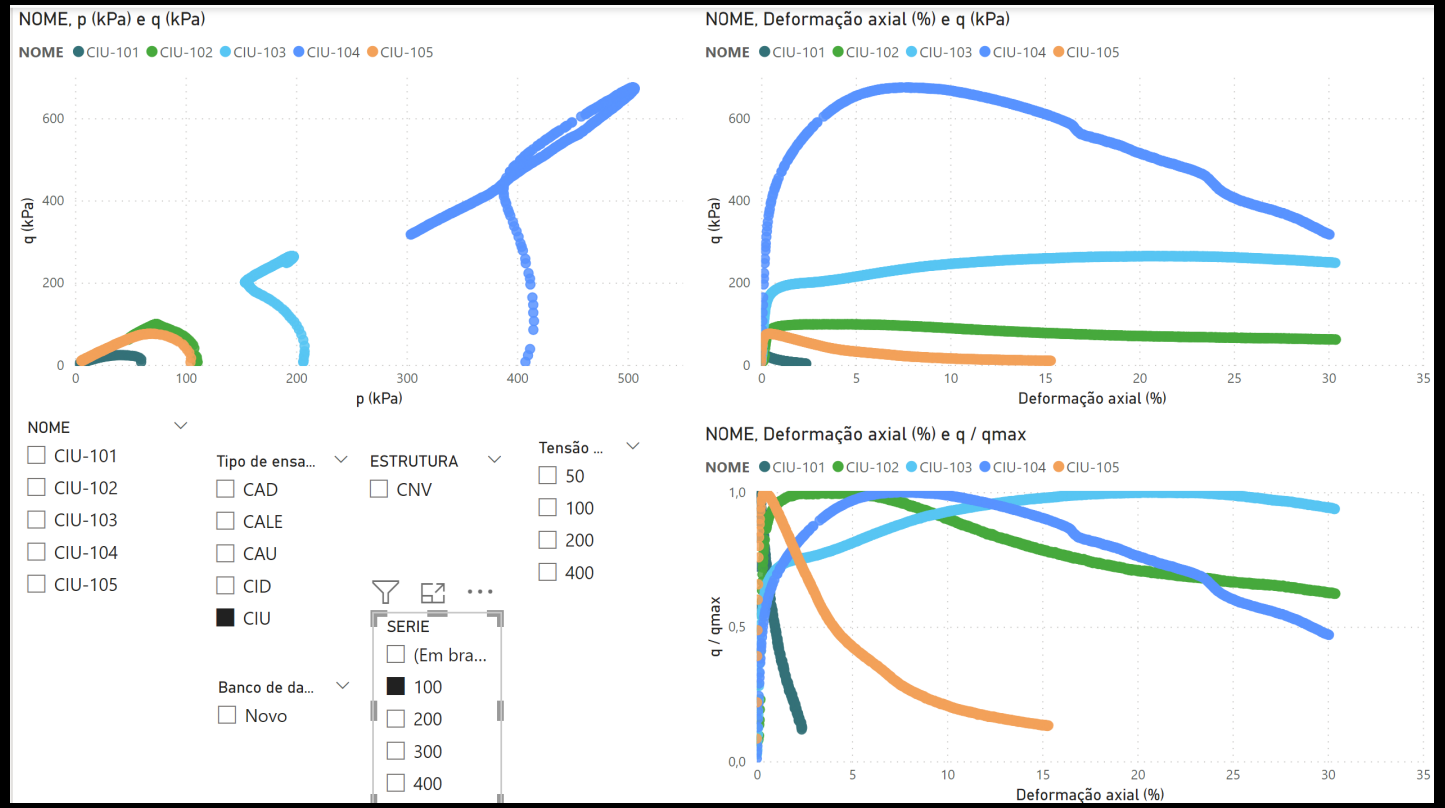
https://www.researchgate.net/figure/Typical-Stress-Strain-Response-in-CAU-test_fig6_328365181

Triaxial Tests with Control of Void Ratio (CIE)

- They control the void index during the test, allowing the evaluation of the compressibility and permeability of the tailings in different states of densification.
- Useful for analysing consolidation and behaviour during dam filling.

Triaxial Tests with Control of Intergranular Pressure (CIU)

- They measure and control the water pressure in the interparticles during the test, providing information on the generation of porewater pressure and the drainage behavior of the tailings.
- Useful for assessing slope stability and liquefaction potential.

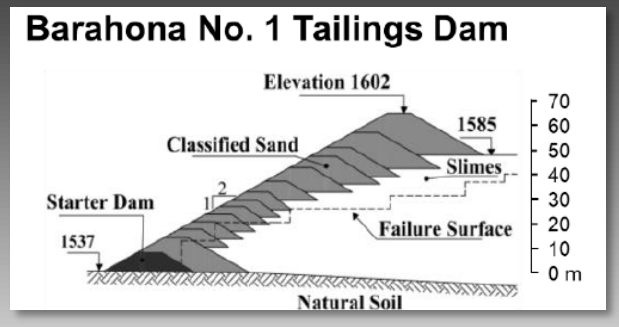


SOURCE: Geocompany files

Triaxial Tests with Control of Inclination Angle and Void Ratio (CALE)

- They combine the advantages of CAU and CIE testing, allowing precise control of the deformation and densification status of the tailings.
- Useful for analyzing the compressive-volumetric behavior and deformability of tailings under different loading conditions.

Emblematic cases



1928 Barahona, Chile (50 fatalities)

1965 El Cobre, Chile (200-350 fatalities)

1994 Merriespruit, S. Africa (17 fatalities)

1998 Aznalcóllar Spain

2014 Mount Poley, Canada

2015 Fundão, Brazil (19 fatalities)

2016 Cadia, Australia

2019 Feijão, Brazil (270 fatalities)

Source: Lessons from tailings dam failures – where to go from here?

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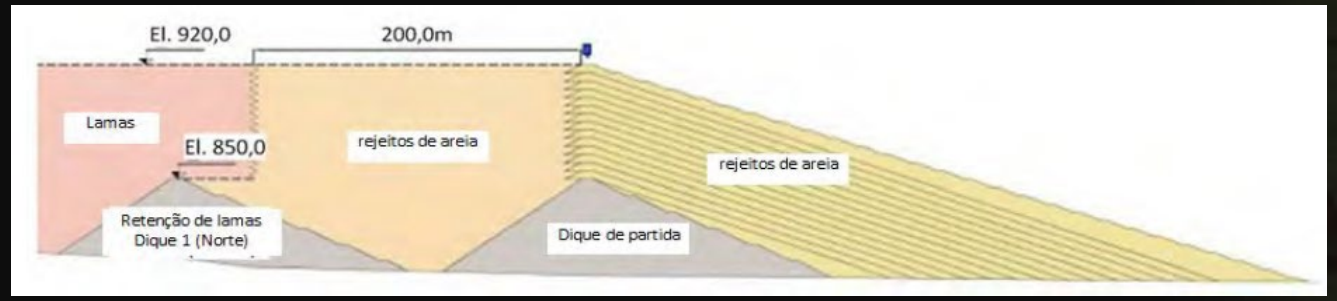
FUNDÃO – MARIANA

NOV /2015

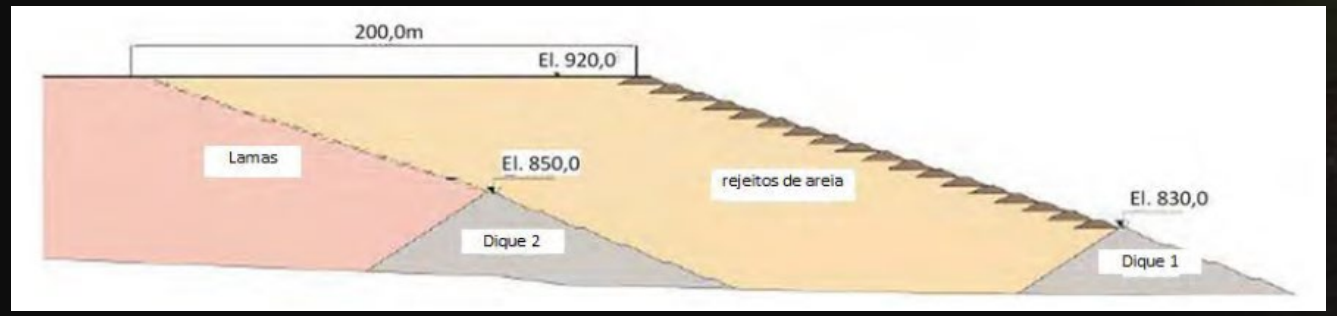
- Liquefaction failure as a consequence of a chain of events and conditions:
  - Change in the original design led to increased saturation
  - Soft sludges advanced into unforeseen areas
  - Sludge beneath the dam subjected to the imposed load from raising
  - Extrusion of sludges and separation of sands as the dam height increased
  - Ground tremors caused a slight increase in load, triggering liquefaction

Image: GloboNews

- Height of 110m
- 2009 occurrence of piping - controlled



Centerline raising considered but not implemented



Upstream raising of Dam 1 using the drained stacking concept

Effects of internal erosion on the slope downstream of Dike 1


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Image © 2024 Maxar Technologies
Google Earth


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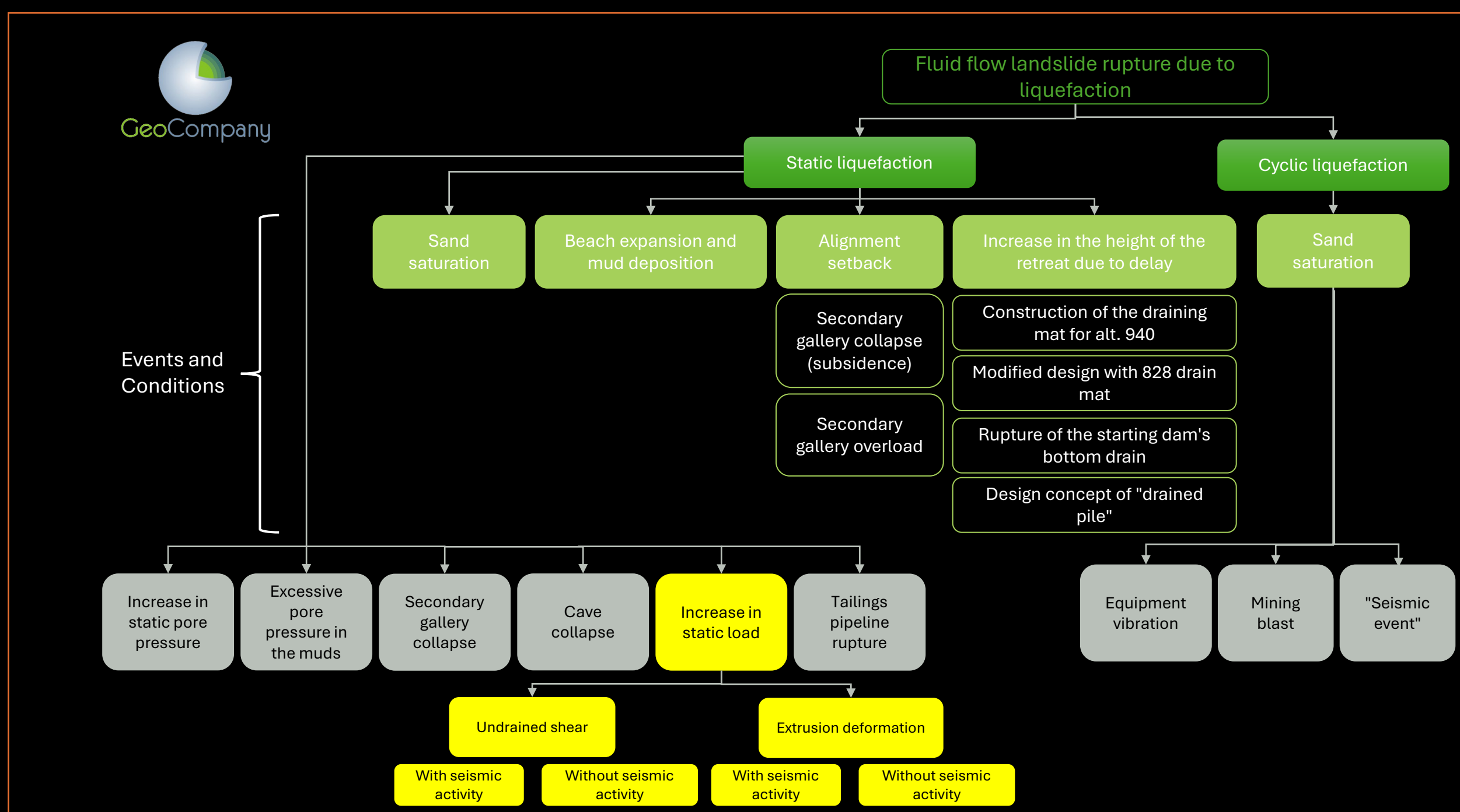
Image © 2024 Maxar Technologies
Google Earth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Fluid flow landslide rupture due to liquefaction
Static liquefaction
Cyclic liquefaction
Events and Conditions
Sand saturation
Beach expansion and mud deposition
Alignment setback
Increase in the height of the retreat due to delay
Sand saturation
Secondary gallery collapse (subsidence)
Secondary gallery overload
Construction of the draining mat for alt. 940
Modified design with 828 drain mat
Rupture of the starting dam's bottom drain
Design concept of "drained pile"
Increase in static pore pressure
Excessive pore pressure in the muds
Secondary gallery collapse
Cave collapse
Increase in static load
Tailings pipeline rupture
Equipment vibration
Mining blast
"Seismic event"
Undrained shear
Extrusion deformation
With seismic activity
Without seismic activity
With seismic activity
Without seismic activity

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BRUMADINHO

JAN/2019

- 272 victims
- 86 m in height and 720 m in crest length
- Tailings area of 250,000 m^2

- Volume of 12 million m^3 of ruptured tailings

https://www.mg.gov.br/pro-brumadinho/pagina/historico-do-rompimento-das-barragens-da-vale-na-mina-corrego-do-feijao#:~:text=Com%20altura%20de%2086%20metros,de%20250%20mil%20metros%20quadrados.

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BRUMADINHO

JAN/2019

https://www.youtube.com/watch?v=IMfLLpA1b5I


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Córrego do Feijão
NOVA
ESTÂNCIA
INN


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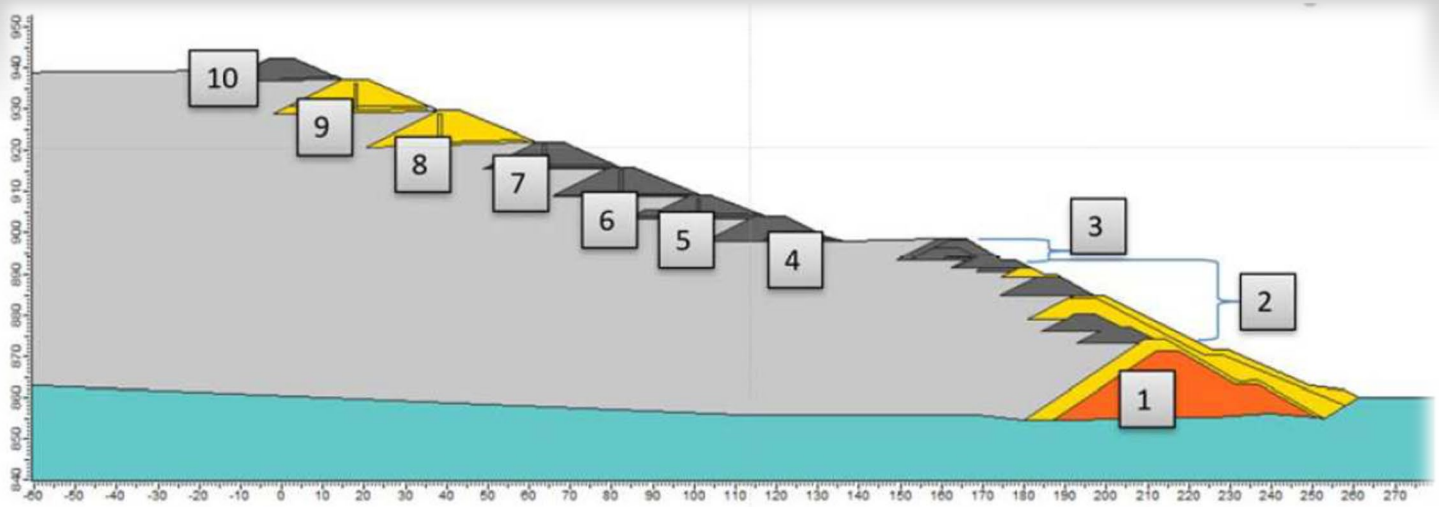
Córrego do Feijão
NOVA
ESTÂNCIA
INN

Brumadinho – Conclusions Expert Panel

PROJECT - steep slope built upstream;

WATER CONTROL IN THE BASIN - the water from the settling pond could reach near the crest of the dam, resulting in the discharge of weak tailings near the crest;

PROJECT SETBACK - pushed the upper parts of the slope onto the weaker fine tailings;



SOURCE: Report of the Expert Panel, 2019

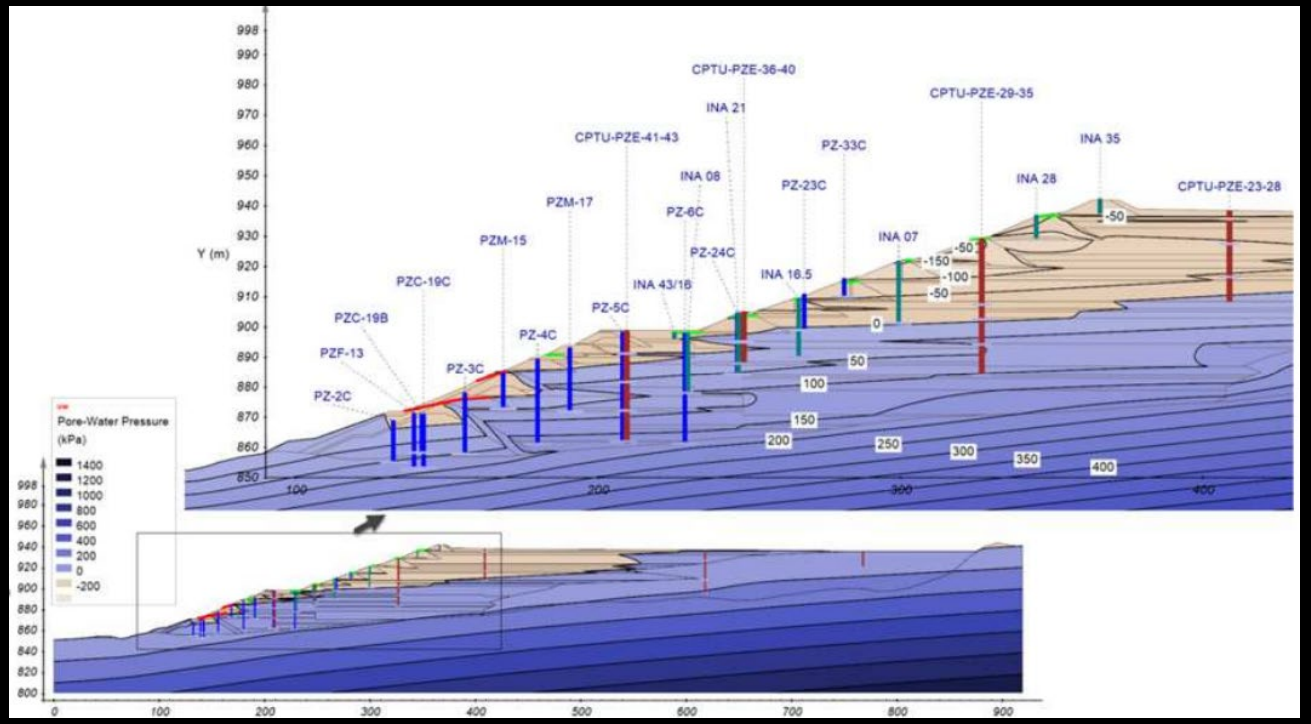
Brumadinho – Conclusions Expert Panel

INTERNAL DRAINAGE LACK

High water level persists in the dam, mainly in the dam toe region;

HIGH IRON CONTENT

Heavy tailings with cementation between particles. This cementation resulted in rigid tailings that exhibited potentially very fragile behavior if subjected to a trigger that caused an undrained response;



SOURCE: Report of the Expert Panel, 2019

Brumadinho – Conclusions Expert Panel

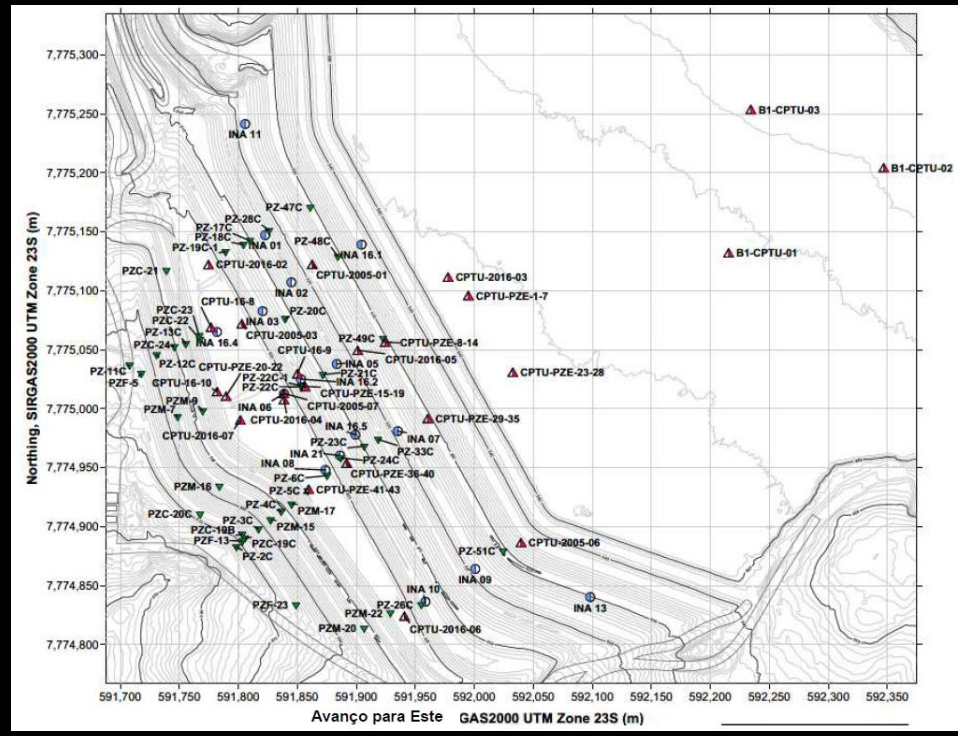
INTENSE REGIONAL PRECIPITATION

Due to the rainy season, which can result in significant suction loss, producing a small loss of strength in unsaturated materials above the water level.

MONITORING

Piezometers / CPTu / Inclinometers / etc

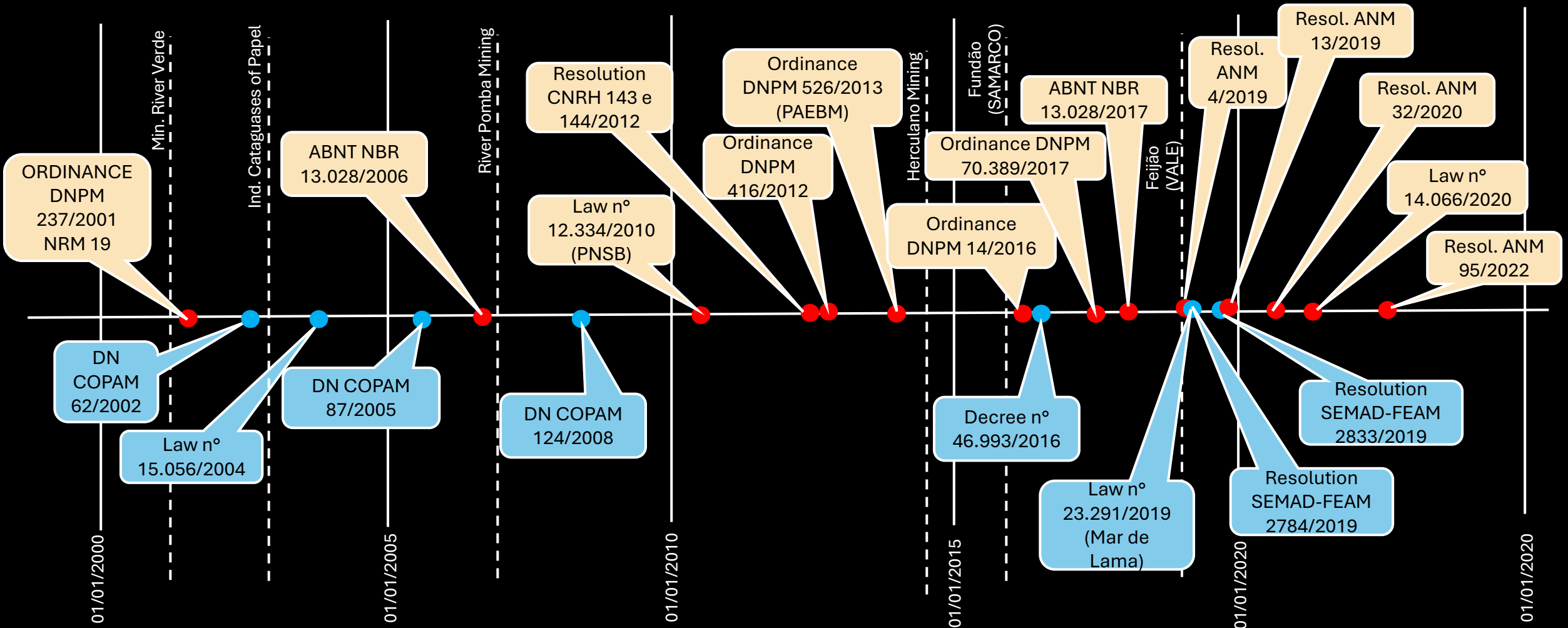
the failure occurred without apparent precursors



SOURCE: Report of the Expert Panel, 2019

Brazilian Legislation and Regulation on Tailings Dams

- Main laws, rules and regulations related to the construction and operation of tailings dams.



SOURCE: Lecture Minas Gerais Society of Engineers – Leandro Quadros Amorin, April 2024

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Dam Safety Legislation

- Law nº 12,334 (2010) establishes the National Policy for Dam Safety and creates the National System of Information on Dam Safety.

- The fundamentals of the NPDS are: The safety of the dam in all phases, from planning to future uses. Encouraging the participation of the population in preventive and emergency measures, including the elaboration and implementation of the Emergency Action Plan (PAE).

CRITERIA TO QUALIFY FOR THE PNSB	
Height	≥ 15 meter
Volume	≥ 3 millions m^3
Residue	= Dangerous
Associated Potential Damage	= Medium or High

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Dam Safety Legislation

- Law nº 14.066 (2020) Revises the PNSB

Prohibition of construction of upstream raised dams

Mandatory PAE - Emergency Action Plan for all dams with high and medium associated potential damage or high risk, including tailings dams

Obligation of controlling companies in case of disasters to repair damage to human life, the environment, and property until the complete decharacterization of the structure

Source: https://mab.org.br/2020/10/01/com-proibicao-de-barragem-a-montante-e-novas-regras-para-mineradoras-lei-que-trata-de-seguranca-e-sancionada/

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Dam Safety Legislation

- Ordinance No. 70,389 (2017) DNPM (ANM) creates the National Registry of Mining Dams and the Integrated Management System in Mining Dam Safety (SIGBM)

- Resolution No. 132 (2016) ANA - Establishes complementary criteria for the classification of dams regulated by ANA regarding the Associated Potential Damage - DPA

Capybara and Jurumin Hydroelectric Power Plant Affected by ANA Resolution 132
source: https://www.gov.br/ana/pt-br/assuntos/noticias-e-eventos/noticias/ana-define-faixas-de-operacao-para-reservatorios-de-hidreletricas-da-bacia-do-rio-paranapanema-pr-sp

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Procedure for Dam Management in Brazil

NR 22 - Occupational Health and Safety in Mining

22.3.4 It is also the responsibility of the company or mining permit holder:
a)....
c) Provide contracted companies with information on potential risks in the areas where they will carry out their activities

22.3.7 It is the responsibility of the company or mining permit holder to develop and implement the Risk Management Program - PGR, covering aspects of this Standard, including, at least, those related to
a) ...
j) Mass stability;

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The Procedure for Dam Management in Brazil

Ordinance 237/2001: Mining Regulations - DNPM (ANM)

22.5.3 The general introductory training must have a minimum duration of 6 hours per day, for 5 (five) days, for underground activities, and 8 hours per day, for 3 (three) days, for surface activities, during working hours, and will have the following minimum curriculum:

a) ...

j) dissemination of existing risks in the work environments included in the Risk Management Program and of accidents and occupational diseases;

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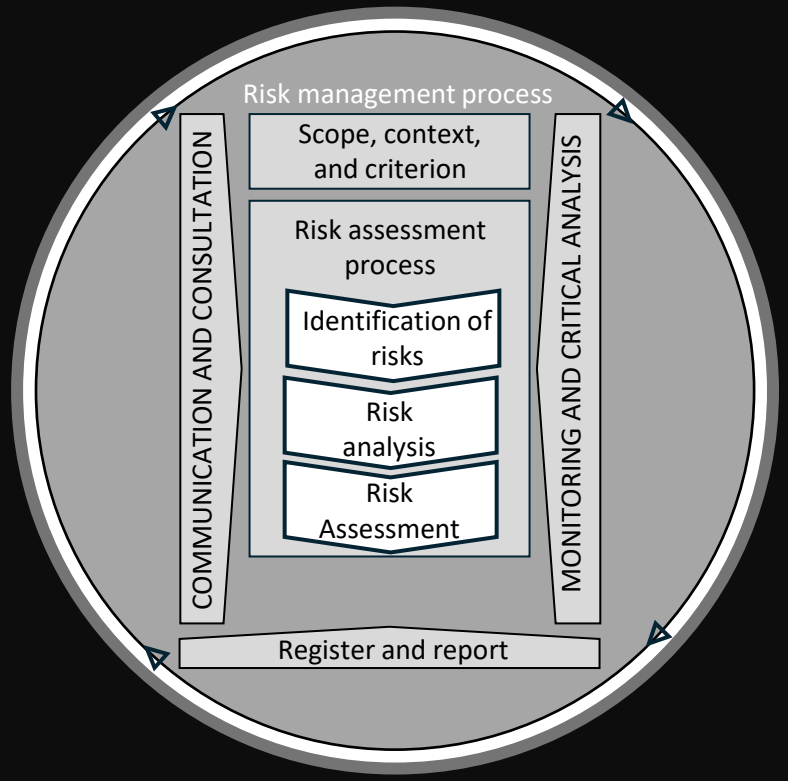
The Procedure for Dam Management in Brazil

ISO 31.000: 2018 - Risk Management Standard

The ISO 31000 is the Risk Management Standard that addresses guidelines and a guide for the implementation of organizational risk management. The Standard is in 2018 version and presents a reference methodology that can be adapted to any subject such as quality, environment, occupational health and safety, anti-bribery, compliance, etc.



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Challenges and Opportunities

- ANM - National Mining Agency
- Intensification of monitoring and oversight measures for the country's dams
- Implementation of preventive and oversight measures
  - Safety reports
  - Emergency action plans
  - Data recording
  - Ongoing dam safety reviews
  - Decommissioning of upstream raised dams

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EOR

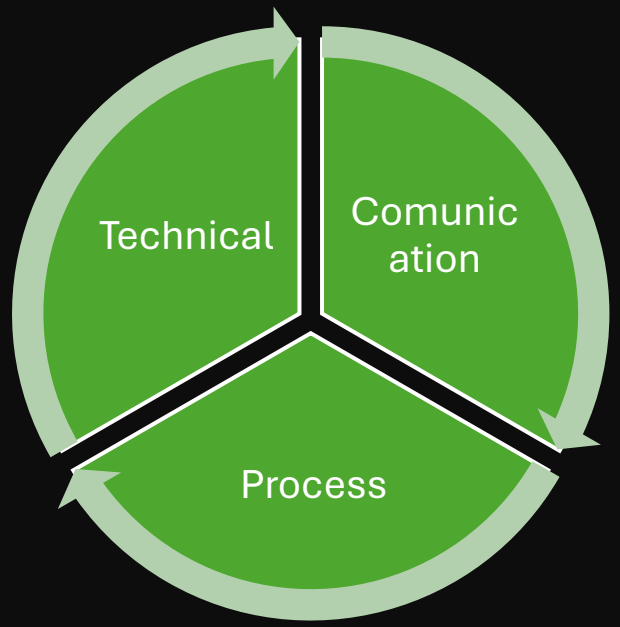
Engineer of Records

Starting in 2020, the implementation of this tool has been in motion.

Legal requirement as of 2022 in Brazil.

A governance tool of great importance that allows an integrated view of facilities.

Pillars of EOR



SOURCE: GeoMin - EoR as a governance tool

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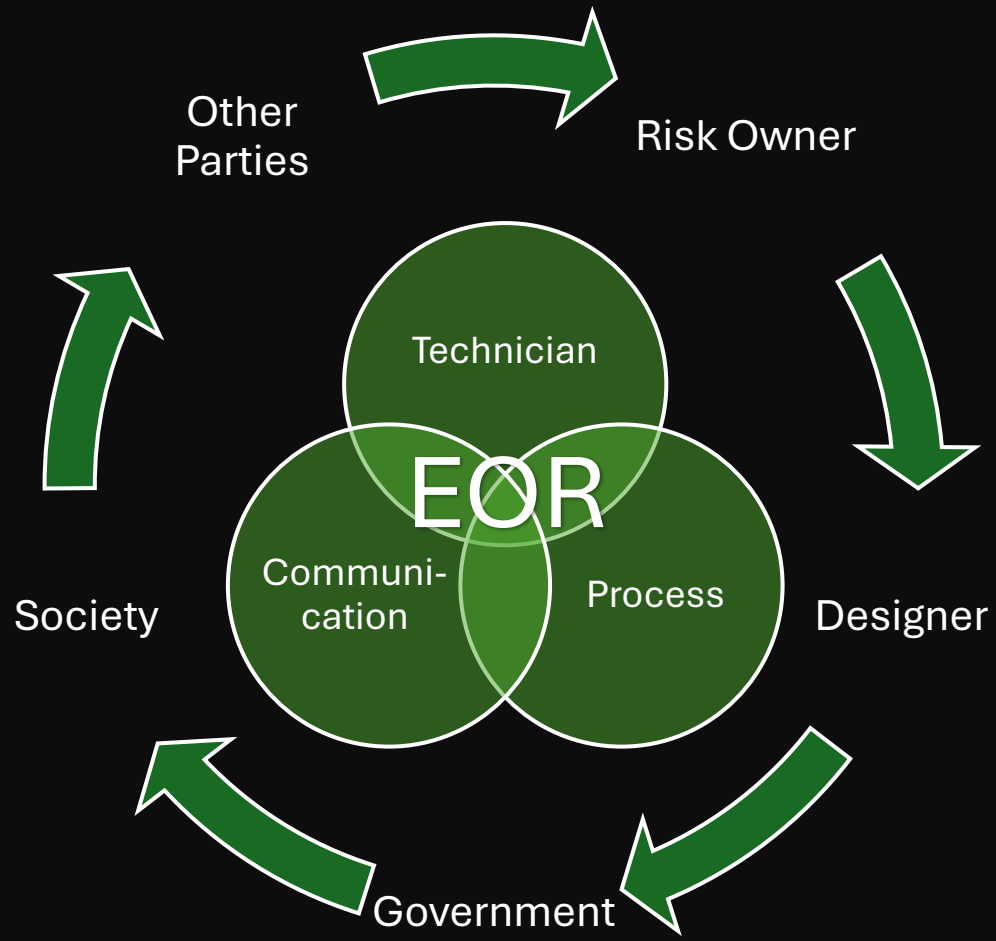
EOR

- Legal entity responsible for the structure
- Function to confirm whether the structure was designed, constructed, and decommissioned in compliance with current regulatory codes and legislation



FONTE: GeoMin - EoR Como ferramenta de governança

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Procedure for Tailings Dam Management in Brazil

Federal (ANM) and State (FEAM) Tailings Dam Audits

Audit	Applicability	Periodicity
RISR (ANM)	All mining dams classified under the National Dam Safety Policy (PNSB) and the Mining Jurisdictional Environmental Control Entities (ECJs)	Semiannual
RTSB (FEAM)	Mining dams located in MG classified under the PESB	Annual for dams with High PDA; Every 2 years for dams with Medium PDA; Every 3 years for dams with Low PDA
RTESB (FEAM)	Upstream raised dams, at emergency levels 2 and 3, and ECJs	Semiannual
RIS (FEAM)	All mining dams classified under the PESB	Semiannual
RPSB (ANM)	All mining dams classified under thePNSB	Every 3 years for dams with High PDA; every 5 years for dams with Medium PDA; every 7 years for dams with Low PDA. 6 months after structural modifications or reclassification of tailings. Before tailings reuse.

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Procedure for Tailings Dam Management in Brazil

Flow of reports in the Mining Tailings Dam Risk Management Process (PGRBM)

Report	Objective	Frequency
Geotechnical Performance Evaluation Report	Present field inspection summary and provide interpretation of the geotechnical assessment of the structure	Monthly
Design Basis Report – DBR	Compile and present project assumptions, technical parameters, and operational constraints in a clear and objective manner, providing a basis for new projects, operation, monitoring, and risk management	Annual and after structural modifications
Alteration Evaluation Report (RAA)	Assess and record the cumulative impact of changes on the level of risks represented by geotechnical structures	Annual and after structural modifications
Hazard Identification and Risk Assessment – HIRA	Reduce risks associated with undesired events to as low as reasonably practicable, by identifying, developing, and specifying controls that prevent the undesired event from occurring or significantly reduce its severity if it does occur.	Annual and after structural modifications
Risk Letter	Present control levels for instrumentation for application in the TARPS (normal, atenção, alerta e emergência)	Annual and after structural modifications

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Prospects for the Future

- Trends and projections for the tailings dam sector in Brazil.
- The importance of sustainability and socio-environmental responsibility in mining.

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Conclusion and Recommendations

- Dams are highly versatile structures, making it possible to use them for various purposes. Therefore, they are extremely important for a country's infrastructure, but they must be monitored as they pose a risk.
- It is necessary to differentiate mining tailings dams that use the upstream raising solution because the structure is of a permanent nature, extending throughout its useful life.
- The use of the upstream raising solution for dams cannot be based on a methodology or technique that reduces the risk to zero or close to it, as such analyses do not exist.
- Although the factor of safety (FS) is extremely important for the elaboration, development, and study of the project in general, relying solely on this requirement is not favorable, as inaccuracies and the use of semi-empirical characteristics may occur.
- In the event of dam failure, criminal liability should be based on technical investigations that determine the causes, without leaving any uncertainties.

Thank you!

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