Ingeniería de Minas
FACULTAD DE CIENCIAS FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE
Educación continua

Diploma en Geomecánica Aplicada al Diseño Minero

9ª. Versión

2024-2025

Módulo 4: Geomecánica en Minería a Cielo Abierto

BHP

Analisis de estabilidad

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02 Octubre 2024

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Auspiciador

GEOBRUGG®

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Safety is our nature

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Introduction

Stability analysis

Compliance with a stability acceptance criteria

- Factor of safety
- Probability of failure
- Size of failure

Scale of analysis

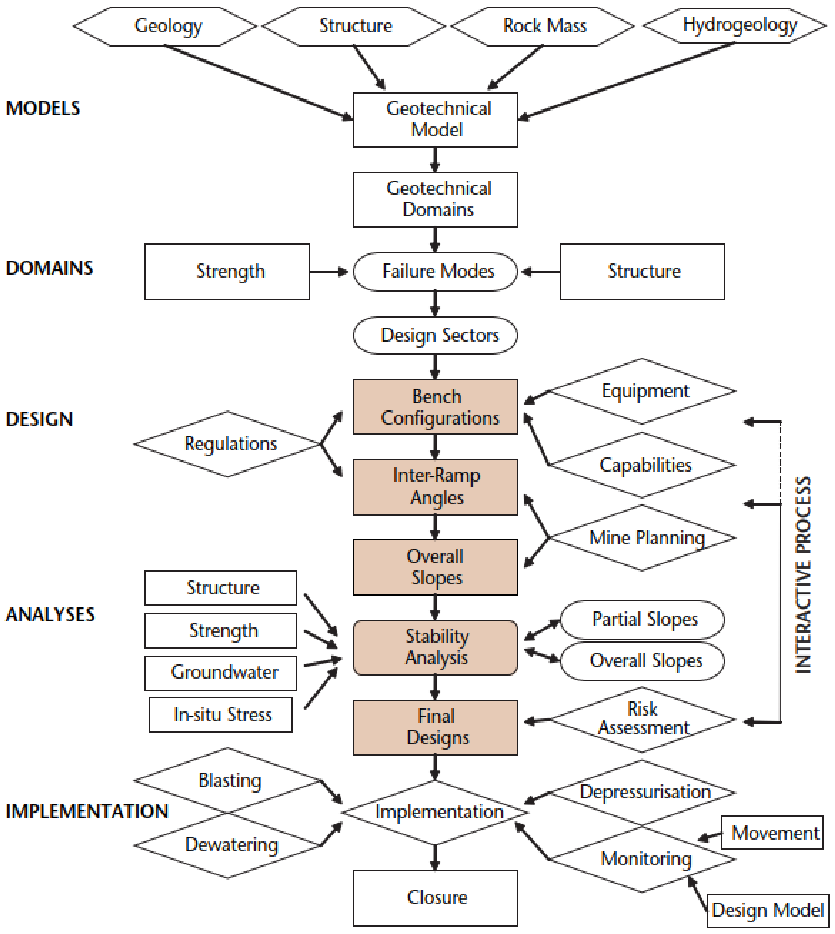
- Bench configuration
- Interramp slope
- Global slope

Techniques

- Limit equilibrium
- Numerical modelling

Outcome

- Final design -> slope geometry



Introduction

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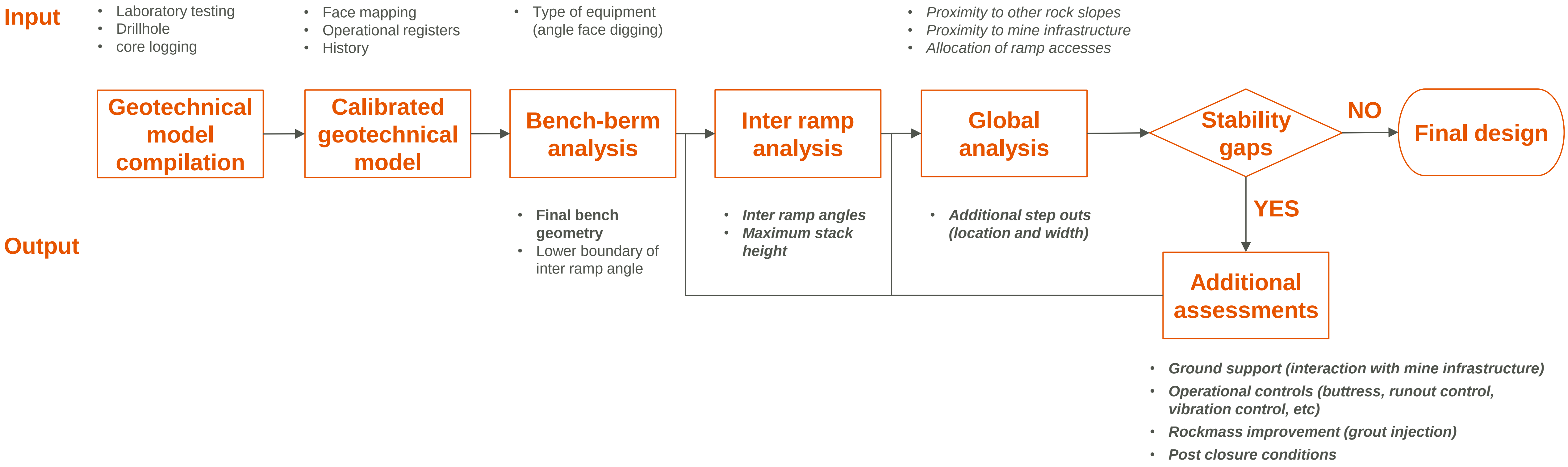
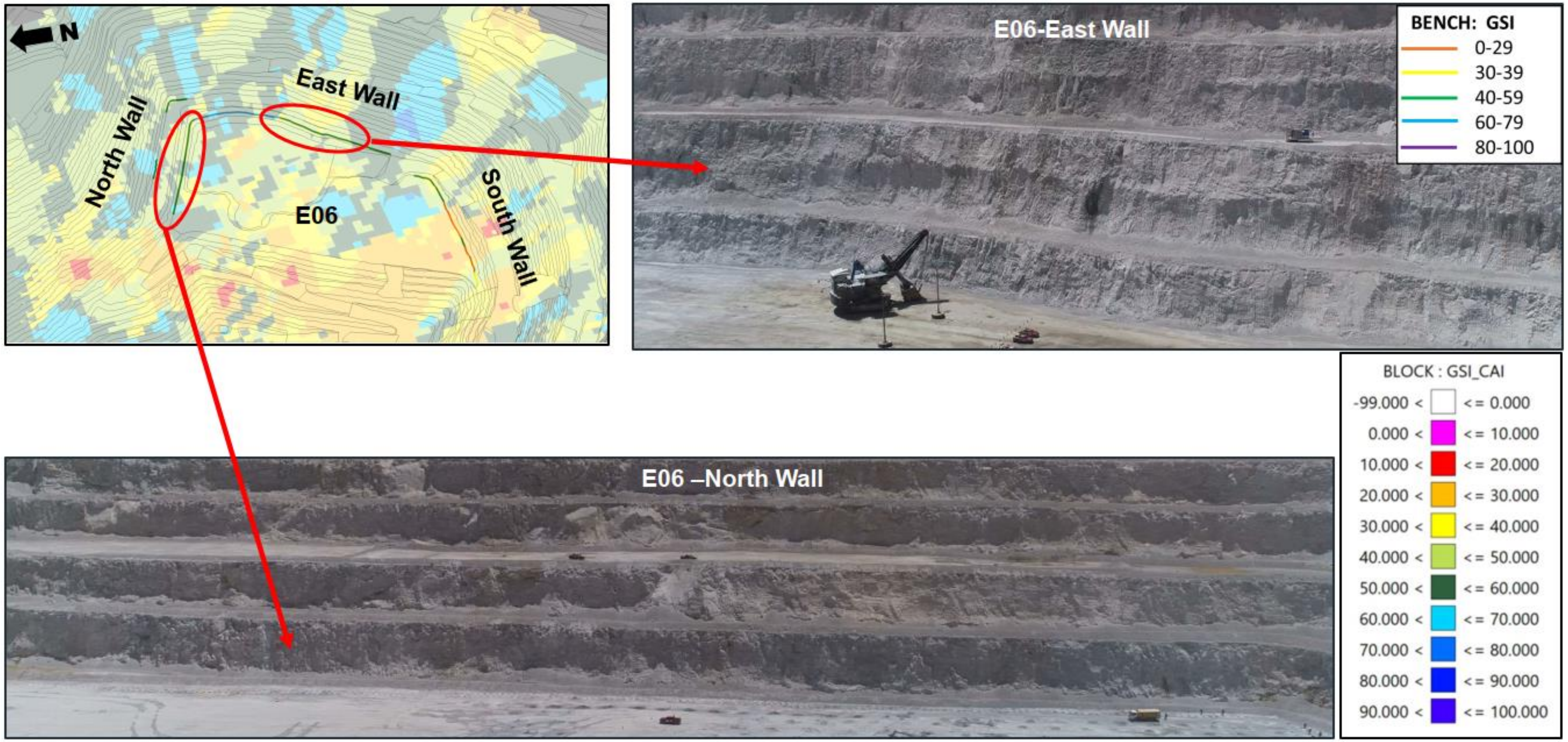
Mining slope design process



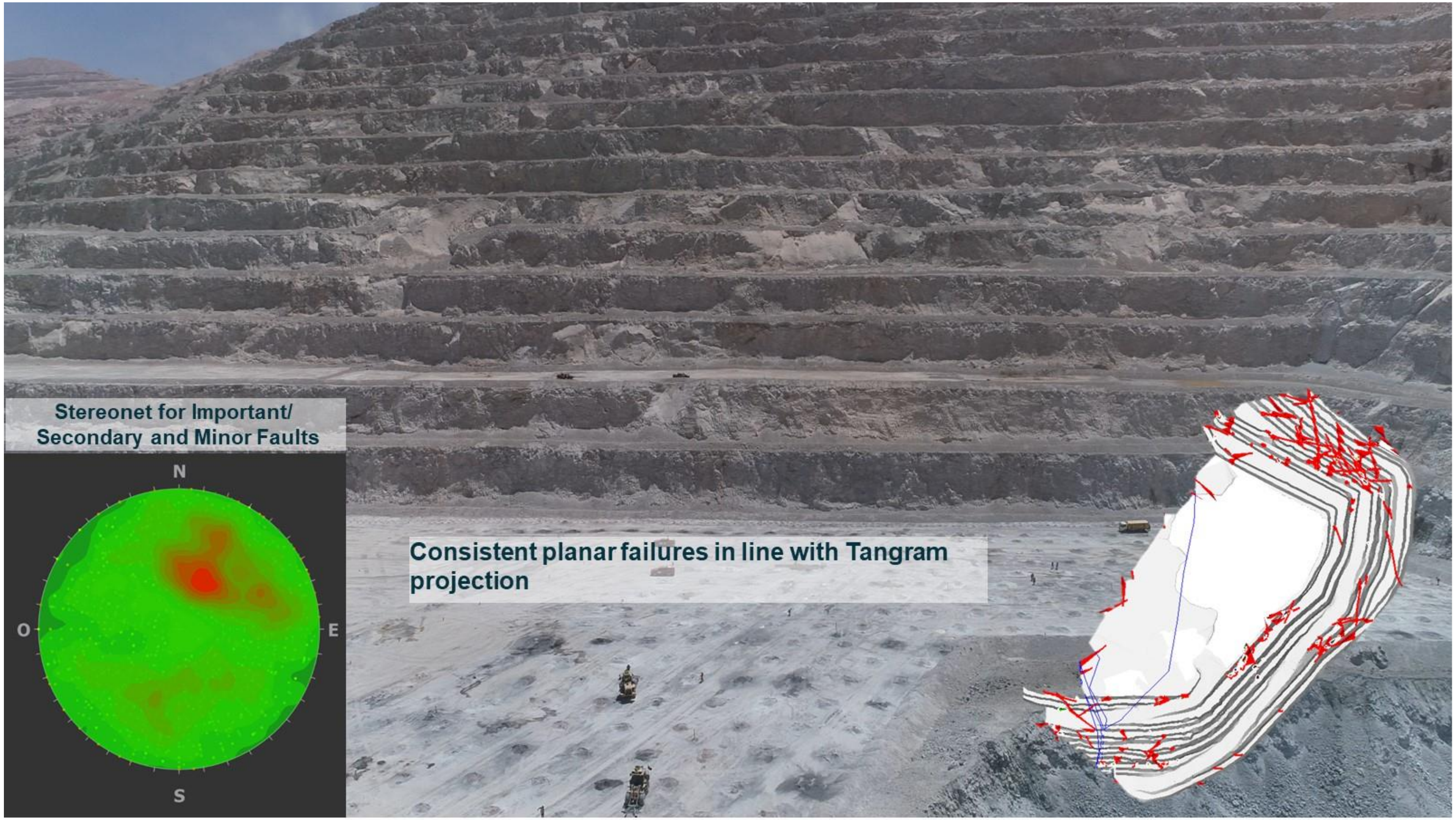
Calibration of geotechnical models

Models vs reality (rockmass classification)



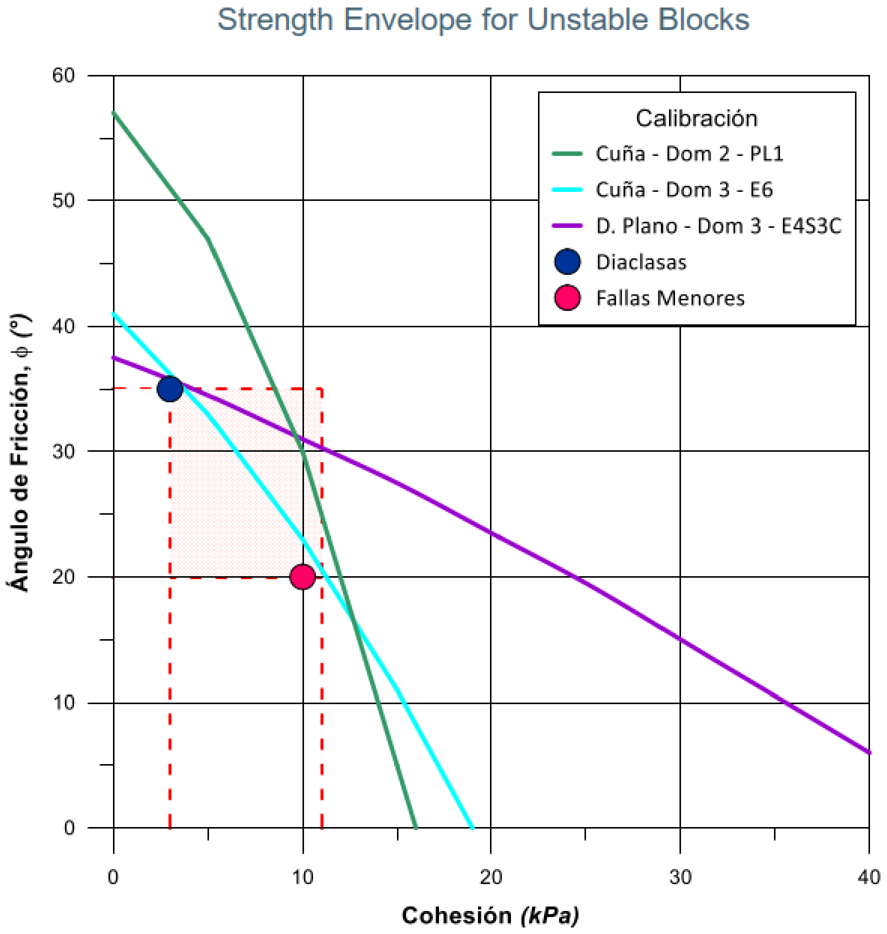
Calibration of geotechnical models

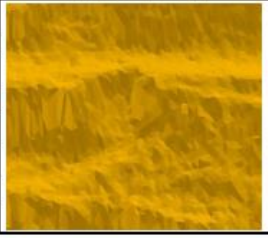
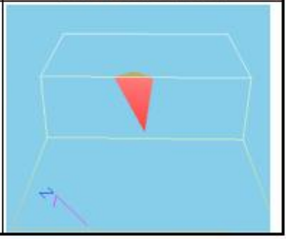
Model vs reality (structural condition)

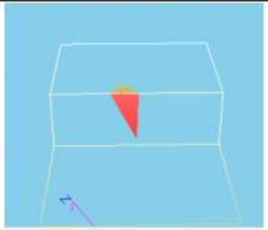


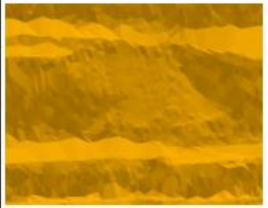
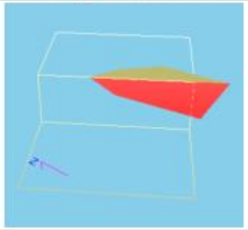
Calibration of properties

Backanalysis



Análisis Retrospectivo				
Geometría del Talud			Dominio 2 - Sector PL1	
	h_b (m)	B (m)	Condición Actual	Bloque modelado
Dominio 2	15	13		
	Dip (°)	Dipdir (°)		
	70	229		
Estructuras				
Set	Dip (°)	Dipdir (°)		
1	69	259		
2	59	198		
3	-	-		

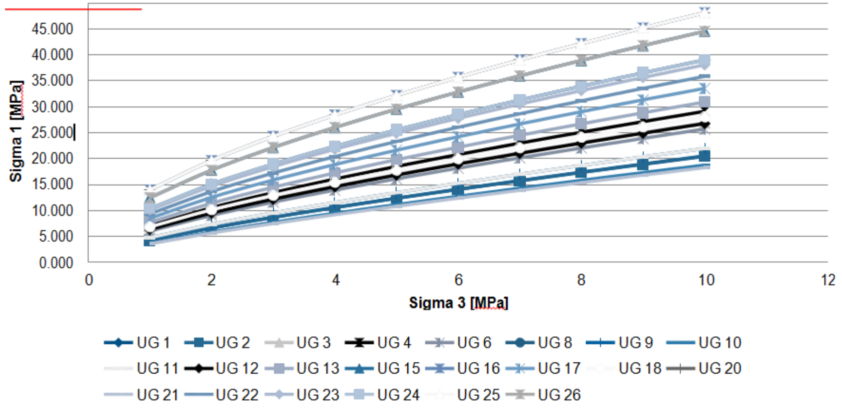
Geometría del Talud			Sector E6	
	h_b (m)	B (m)	Condición Actual	Bloque modelado
Dominio 3	15	13		
	Dip (°)	Dipdir (°)		
	65	221		
Estructuras				
Set	Dip (°)	Dipdir (°)		
1	69	262		
2	53	165		
3	-	-		

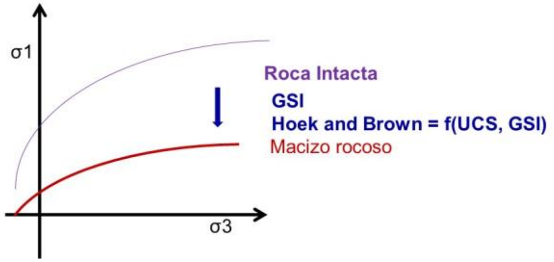
Geometría del Talud			Sector E4S3C	
	h_b (m)	B (m)	Condición Actual	Bloque modelado
Dominio 3	15	12		
	Dip (°)	Dipdir (°)		
	65	245		
Estructuras				
Set	Dip (°)	Dipdir (°)		
1	38	234		
2	40	217		
3	56	264		

Calibration of properties

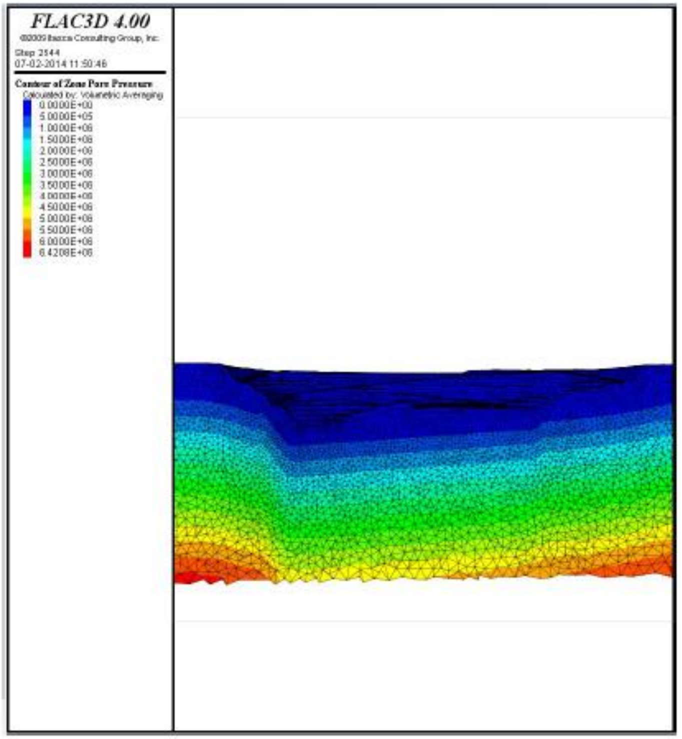
Geotechnical units and mechanical properties

Failure envelopes



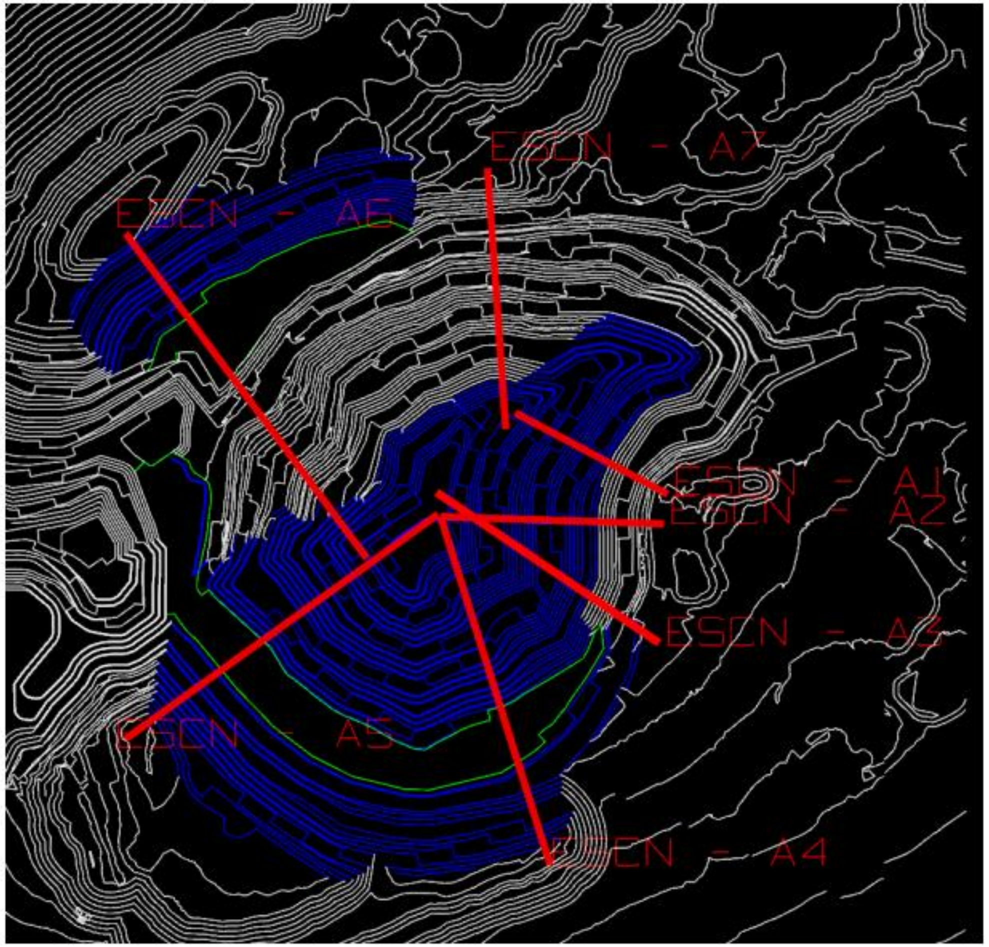


Pore pressures

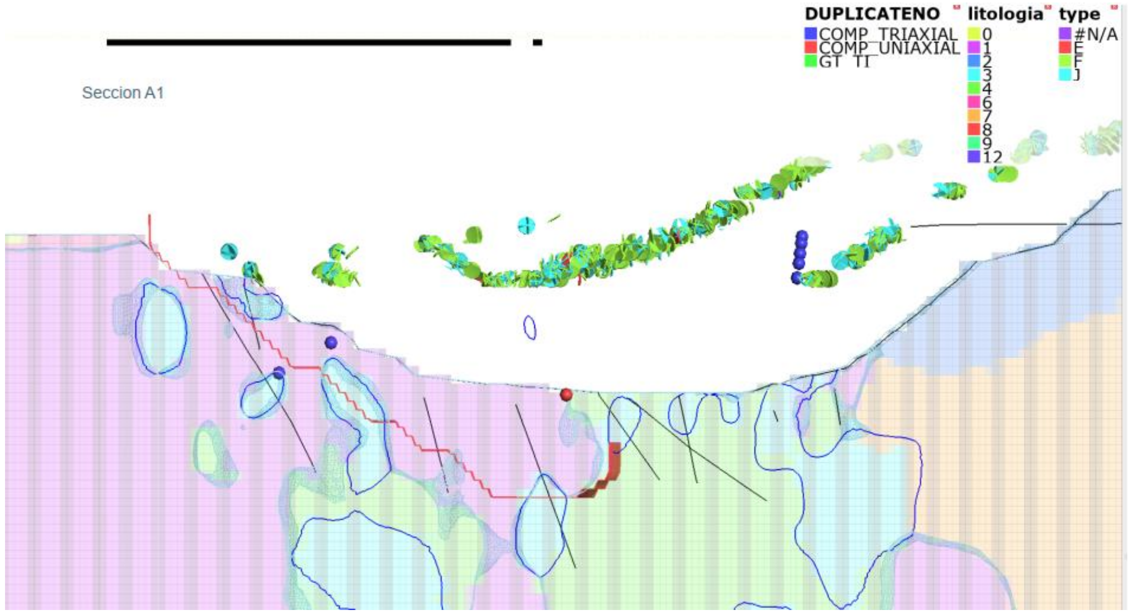


Calibration of geotechnical models

Master sections

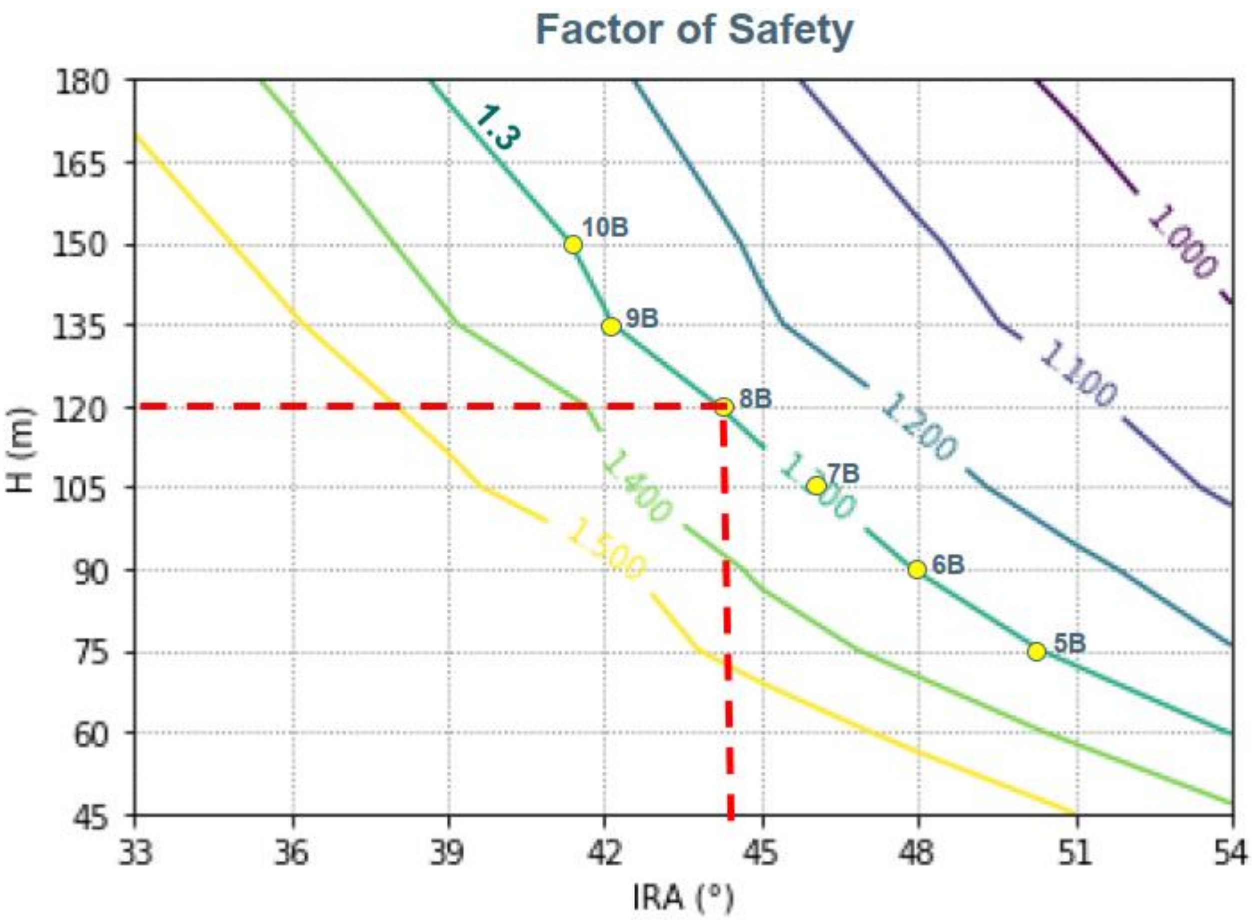


- Visualisation of all available data and reconciliation of reality vs models
- Representative of expansions (mine sequence) in terms of orientation, geotechnical units, structural conditions and ground water.

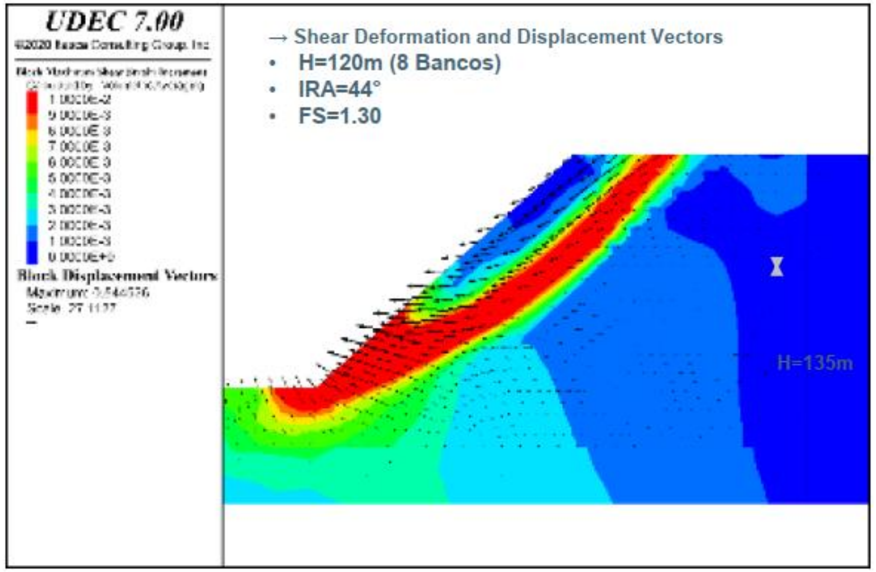


Inter ramp analysis

Design curves



Porphyry Feldspar		
Parameter	Value	Observation
GSI	25	Representative value
UCS	28 MPa	Estimated value based on PLT
Mi	9	Estimated value
D	0.5	Damage conditions



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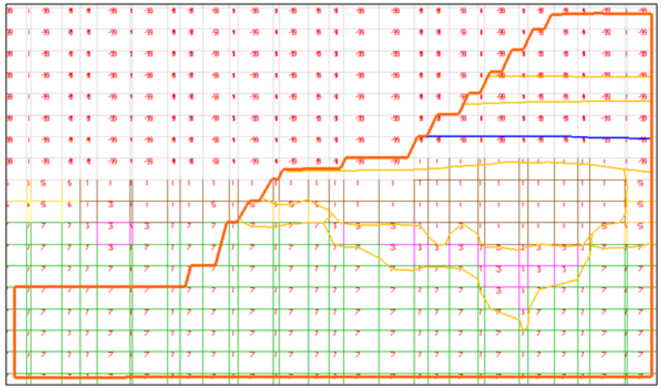
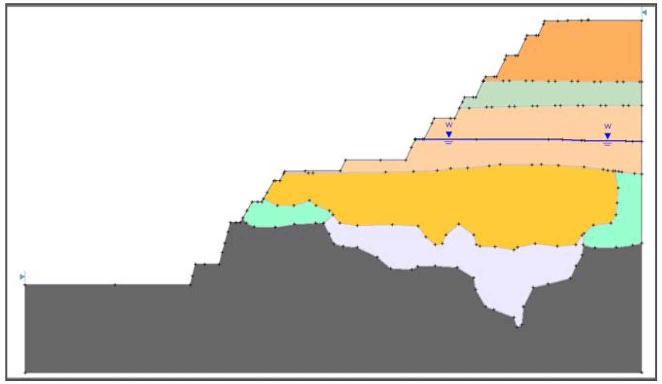
2D Global analysis

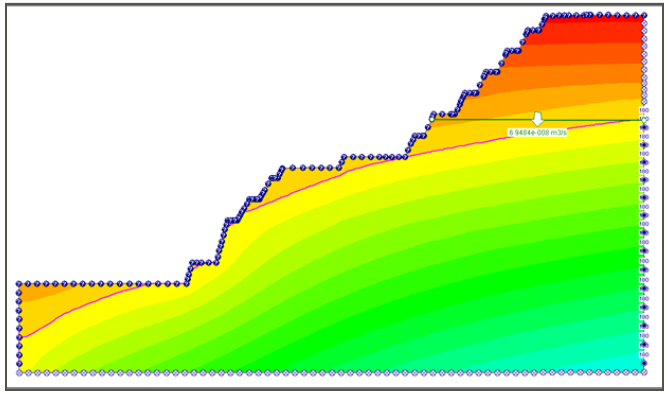
Building blocks



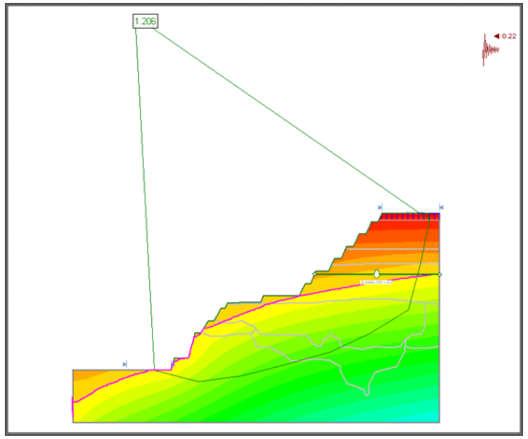
Geotechnical units (block model)



Geotecnical section (geotechnical unit + piezometric line)



Numerical estimation of pore pressures

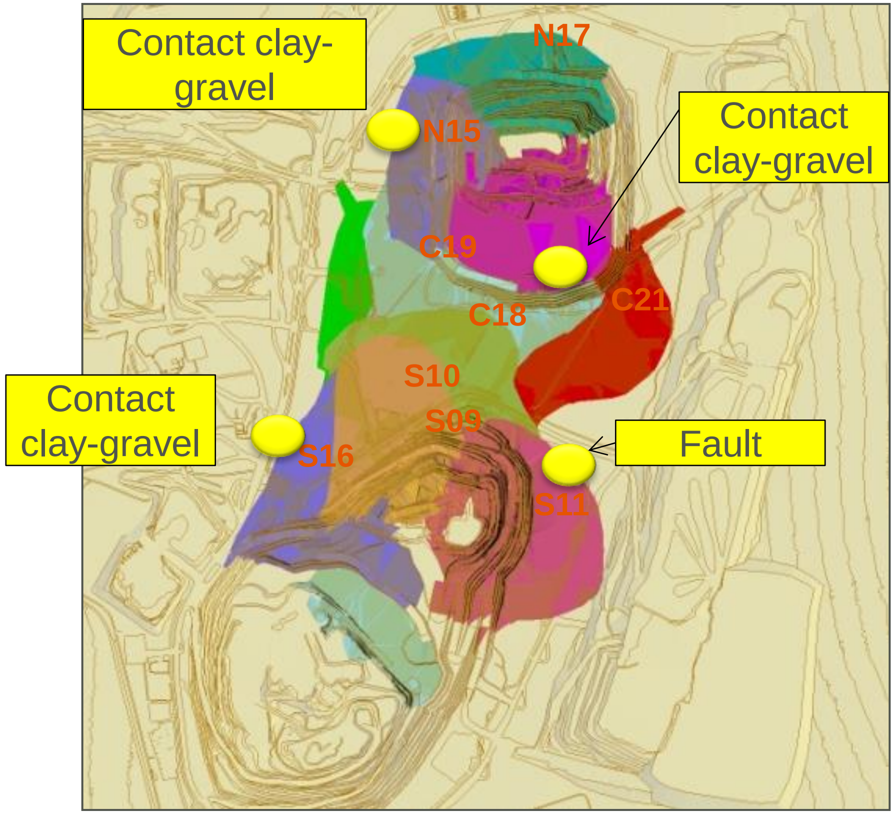


Global stability analysis (example for 0.22g pseudo-static loads)

BHP

2D Global analysis

Mine sequence



Casos		Factor de Seguridad	
		Probabilidad de Falla	FS
Estático	S09	0,6%	2,24
	N14	0,1%	2,29
	N15	20,9%	1,30
	S10	8,3%	1,62
	S16	4,3%	1,85
	S11	1,8%	1,60
	C18	1,2%	1,76
	C19	6,4%	1,56
	N17	11,7%	1,53
	C20	2,8%	1,94
	C21	4,6%	1,71
	FASE_13	0,1%	2,37
Sismo operacional	S09	1,3%	1,94
	N14	0,7%	1,90
	N15	33,2%	1,15
	S10	17,7%	1,37
	S16	9,9%	1,53
	S11	8,9%	1,33
	C18	6,4%	1,45
	C19	16,0%	1,31
	N17	20,4%	1,32
	C20	8,5%	1,59
	C21	13,4%	1,39
	FASE_13	0,4%	1,96
Sismo máximo	S09	0,0%	1,66
	N14	3,5%	1,55
	N15	60,3%	0,92
	S10	32,5%	1,16
	S16	20,8%	1,27
	S11	33,0%	1,09
	C18	25,8%	1,16
	C19	38,4%	1,08
	N17	34,8%	1,13
	C20	19,4%	1,30
	C21	35,8%	1,11
	FASE_13	2,4%	1,59

2D Inter ramp and global Analysis

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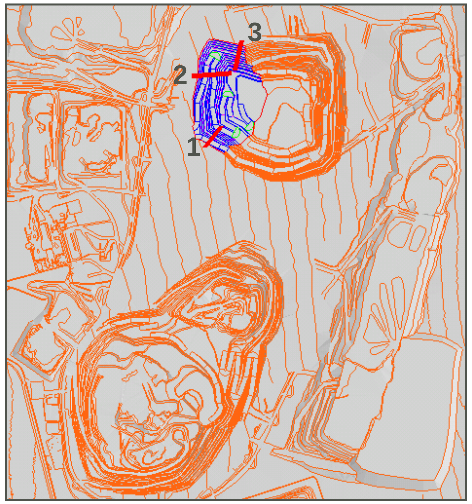
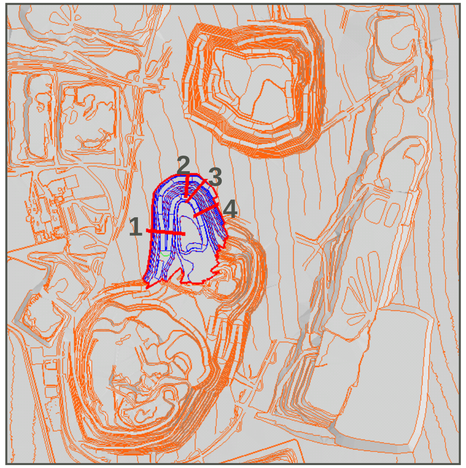
Inter ramp and global stability assessment



Fase	Perfil	Talud	Altura H (m)	Angulo (°)	Peso W (KN/m)	Estático: Factor de Seguridad FS	Peso W (KN/m)	Sismo Operacional: Factor de Seguridad FS	Peso W (KN/m)	Sismo Máximo: Factor de Seguridad FS
N15	p01	Global	190	39	110	1,549	123	1,303	117	1,057
		Inter-Rampa	48	45	15	1,526	15	1,302	12	1,026
		Inter-Rampa	116	52	104	1,525	108	1,306	123	1,135
	p02	Global	201	48	119	1,298	143	1,152	129	0,921
		Desacople	66	45	14	1,513	15	1,294	15	1,082
		Desacople	135	51	92	1,333	97	1,164	90	0,999
	p03	Global	115	37	90	1,820	80	1,493	85	1,243
		Inter-Rampa	102	43	84	1,841	79	1,528	84	1,270
		Desacople	39	48	14	1,517	14	1,318	15	1,111

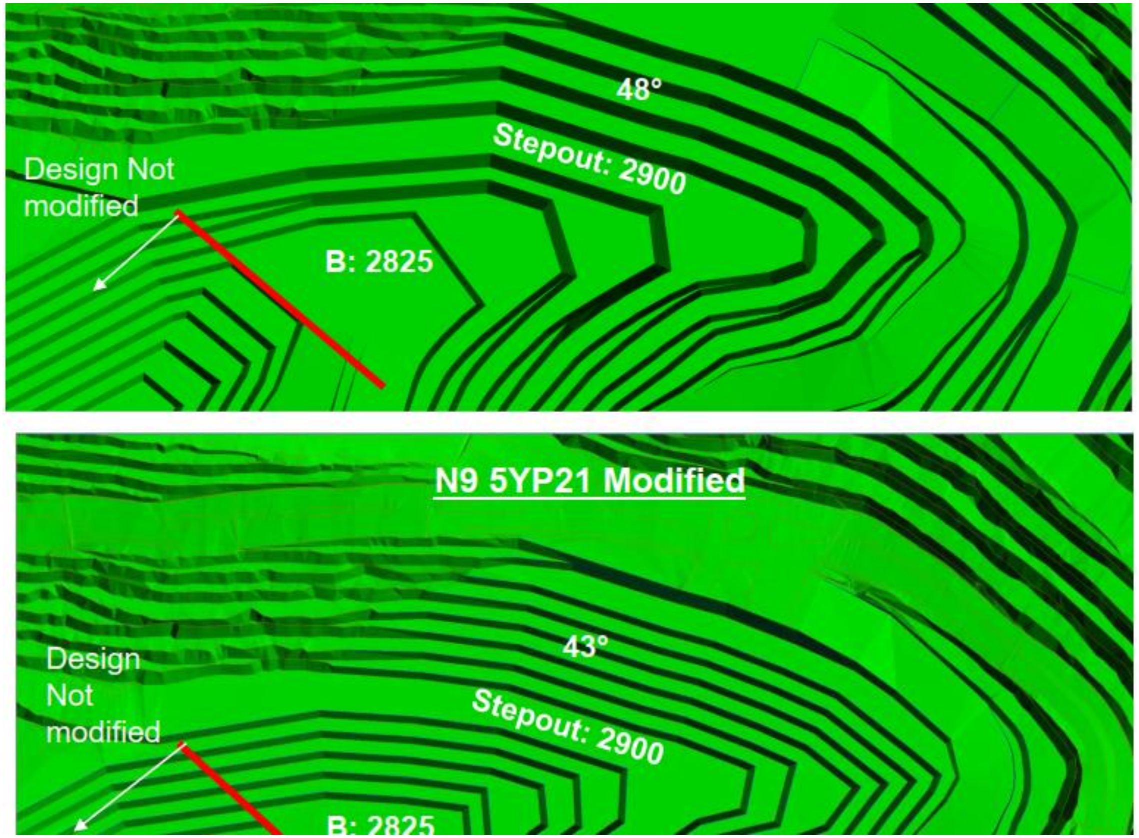


Fase	Perfil	Talud	Altura H (m)	Angulo (°)	Peso W (KN/m)	Estático: Factor de Seguridad FS	Peso W (KN/m)	Sismo Operacional: Factor de Seguridad FS	Peso W (KN/m)	Sismo Máximo: Factor de Seguridad FS
S10	p01	Global	185	38	150	1,598	158	1,333	143	1,092
		Inter-Rampa	65	42	54	3,258	55	2,696	56	2,187
		Inter-Rampa	90	53	84	1,725	83	1,475	78	1,299
		Desacople	50	45	13	1,631	14	1,404	14	1,167
	p02	Global	182	38	124	1,757	121	1,458	114	1,185
		Inter-Rampa	117	45	82	2,219	80	1,881	81	1,560
		Desacople	40	48	8	1,707	8	1,476	9	1,249
	p03	Global	187	38	111	1,797	112	1,477	108	1,213
		Inter-Rampa	138	45	79	2,023	74	1,882	79	1,567
		Desacople	55	47	12	1,505	13	1,306	13	1,091
		Desacople	82	47	52	2,171	50	1,927	50	1,625
	p04	Global	204	39	107	1,617	113	1,374	111	1,160
		Inter-Rampa	96	50	65	2,033	72	1,823	70	1,593
		Desacople	69	47	15	1,454	15	1,230	16	1,032

2D Inter ramp and global analysis

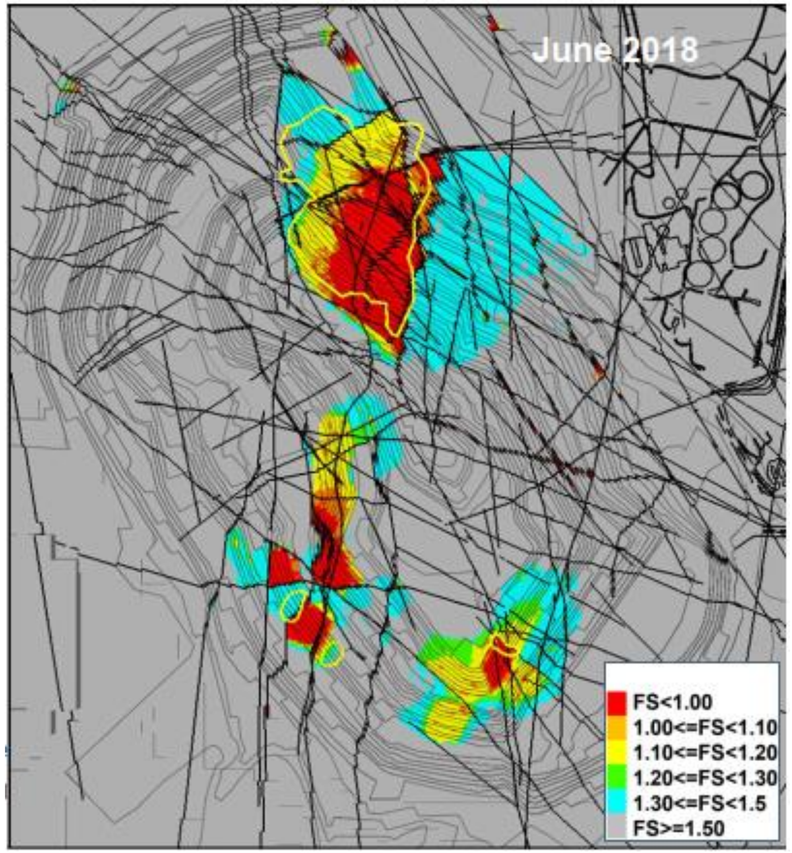
Lower global factor of safety

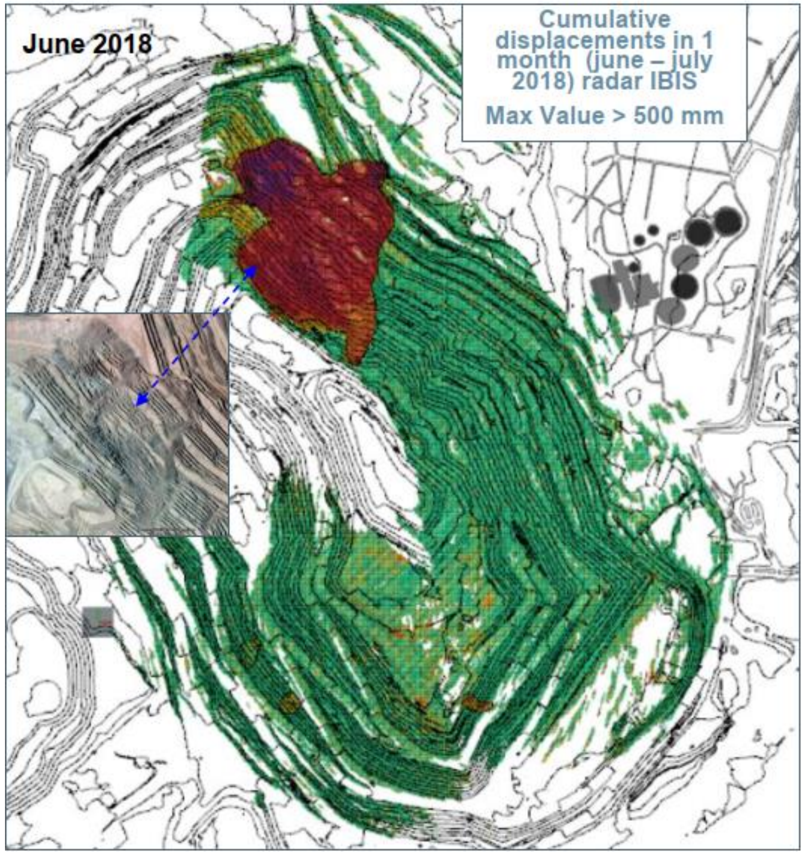
- A lower global factor of safety may require additional design steps.
- If inter ramp walls are found stable, step outs can be allocated to flatter global angle to increase the factor of safety.
- If also inter ramp wall was found unstable, berm width can be increased to flatter inter ramp angle.
- If both inter ramp and global factor of safety is found, combining options can be generated and an economic evaluation to determine which combination (berm width and step out size) is optimum.



3D Inter ramp and global analysis

Numerical model calibration





Source of information for calibration:

- History of past wall failures
- Instrumentation provides history of deformation

Model calibration:

- Replicate historical past failures
- Replicate level of deformation

Type of calibration

- Geotechnical model input (eg, structure driving failure)
- Numerical inputs (eg, properties)

3D Inter ramp and global analysis

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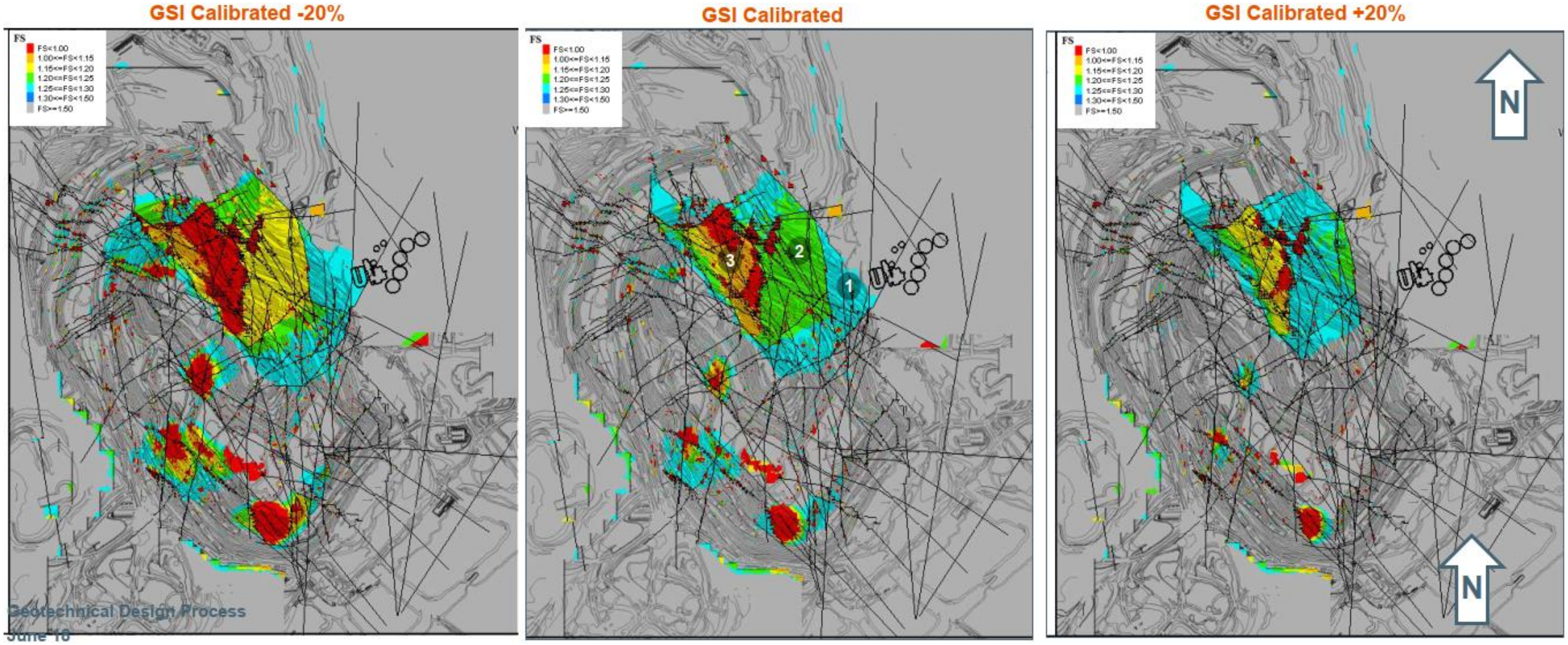
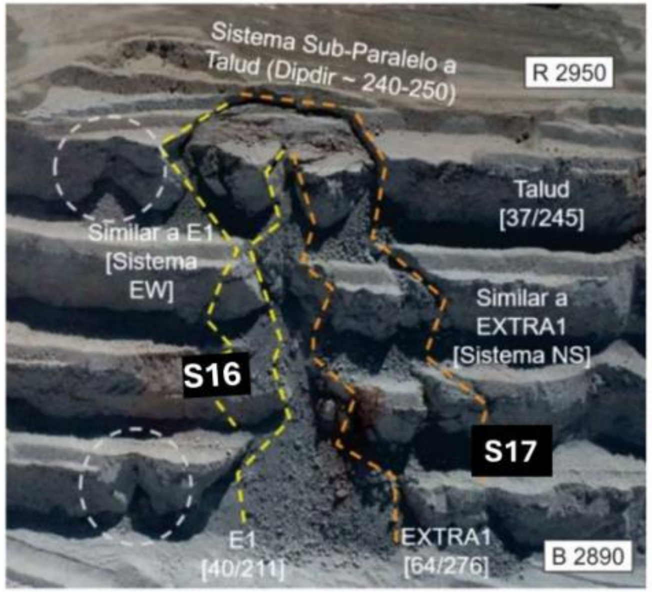
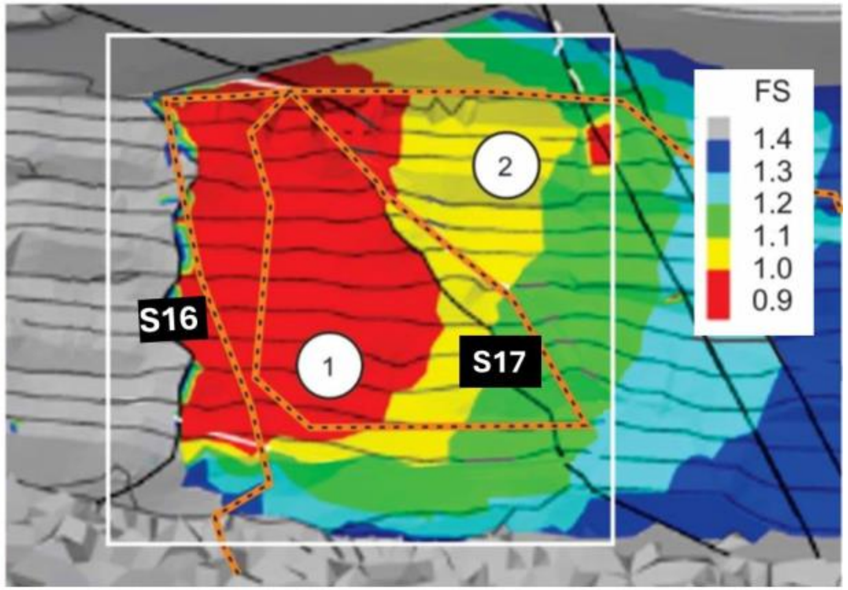
Numerical model calibration GSI ± 20%



3D Inter ramp and global analysis

Numerical model calibration replicating failure mechanism

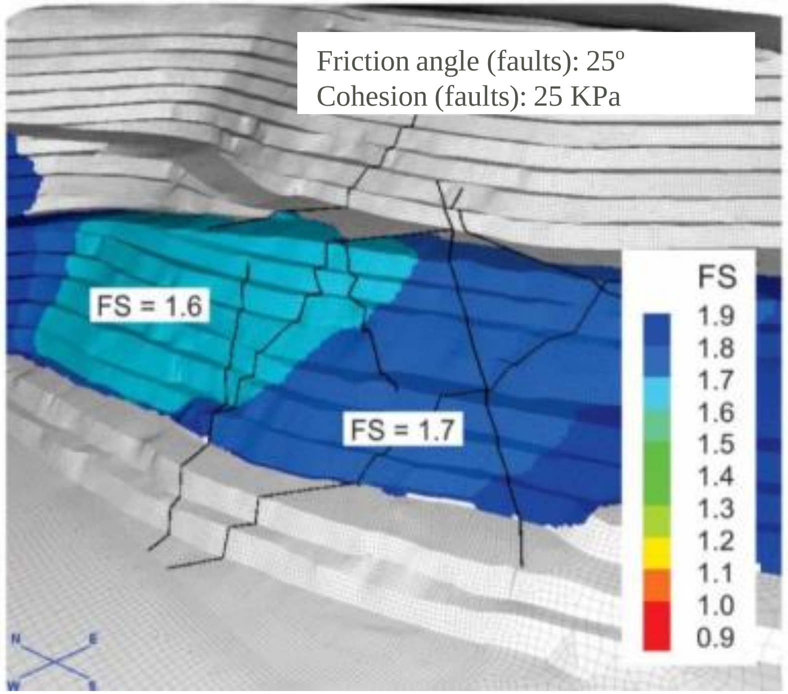


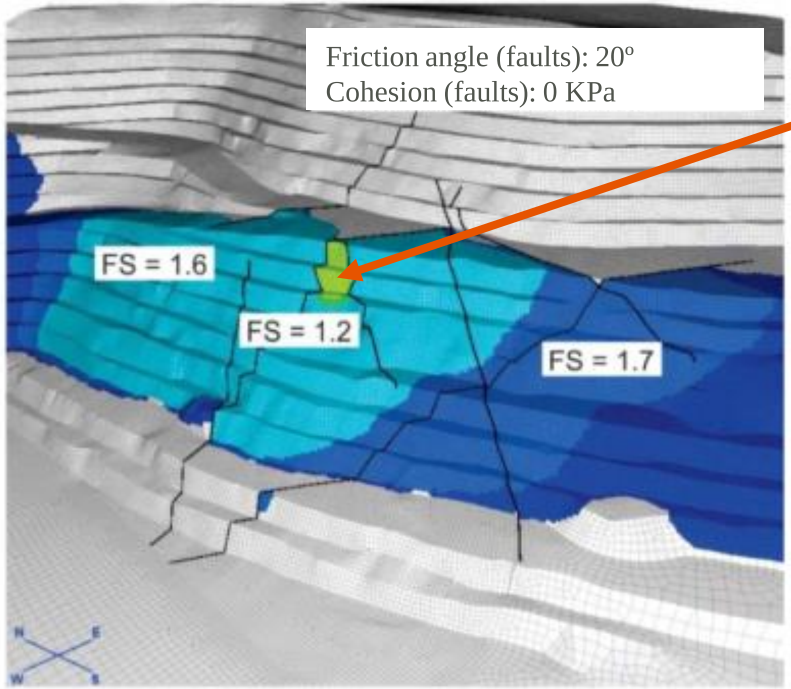


Explicit structures and their properties can be added to the model to better replicate a failure mechanism.

3D Inter ramp and global analysis

Influence of faults in the numerical model

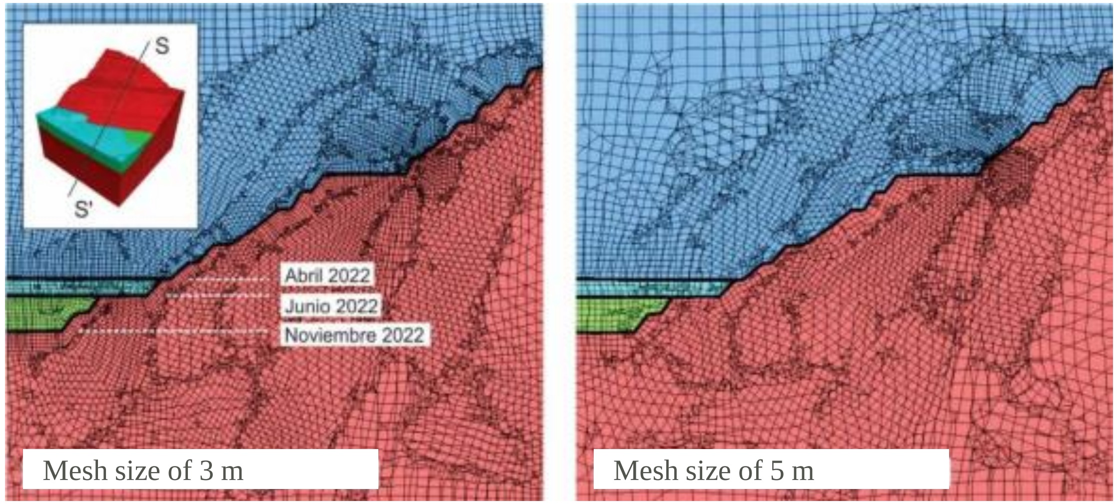




Failure mechanism due to lower properties of fauls

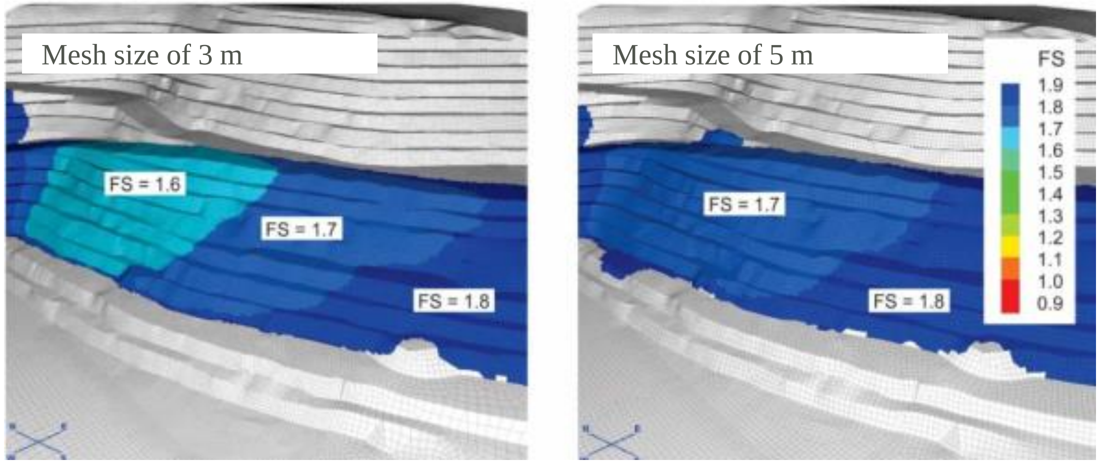
3D Inter ramp and global analysis

Influence of numerical model setting



Main aspects:

- Mesh size: Coarser mesh may hide potential failures due to 3D geometry aspects, areas of litho contacts, faults.
- Boundary limits: size of the model enough to avoid boundary limit effects introducing artifacts.



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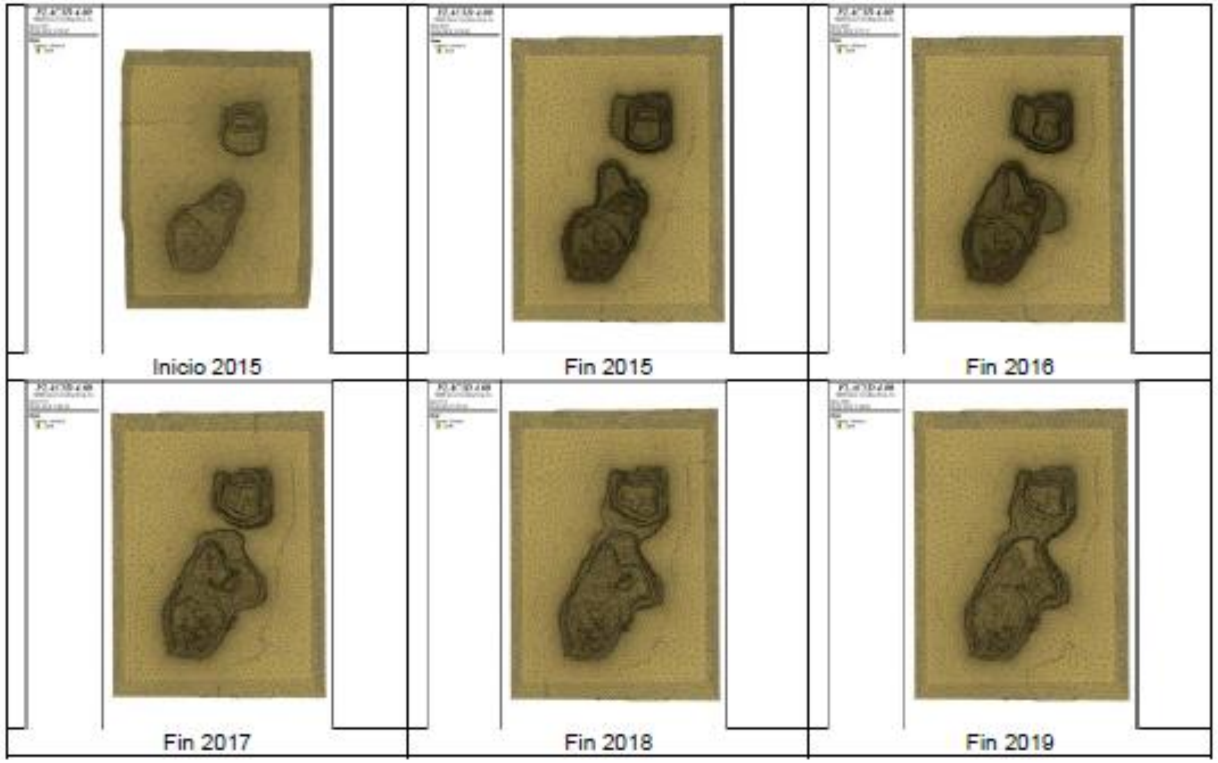
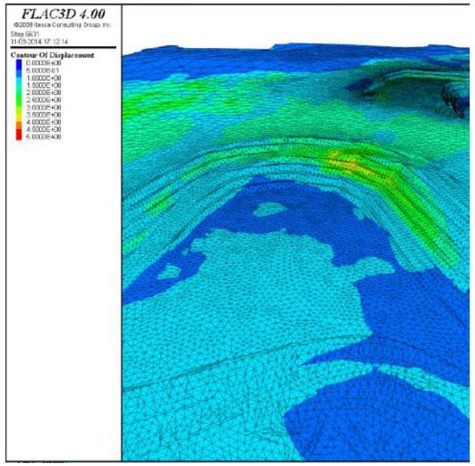
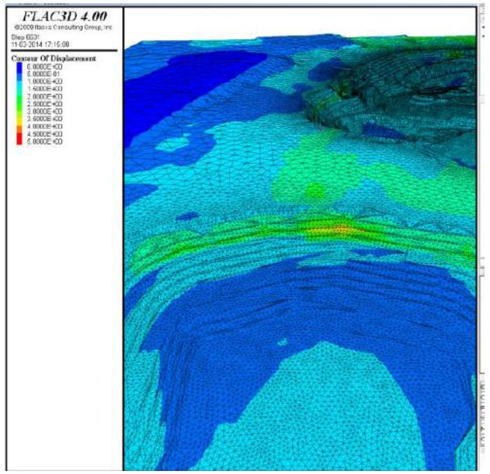
3D Inter ramp and global analysis

Target to feed monitoring plan

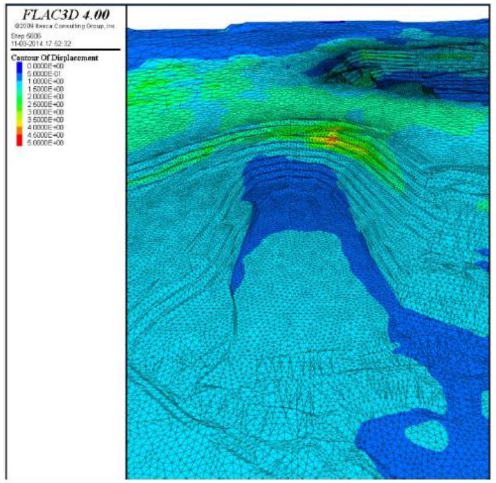


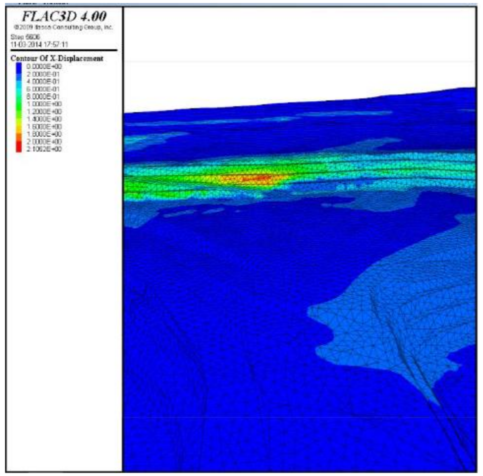
Target areas during FY15





Target areas during FY16

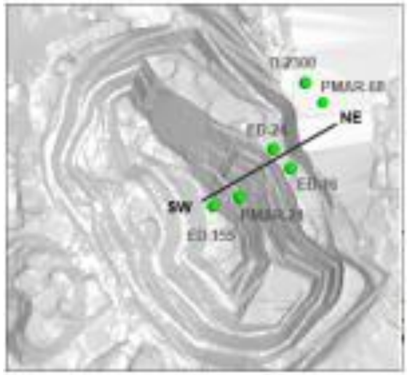


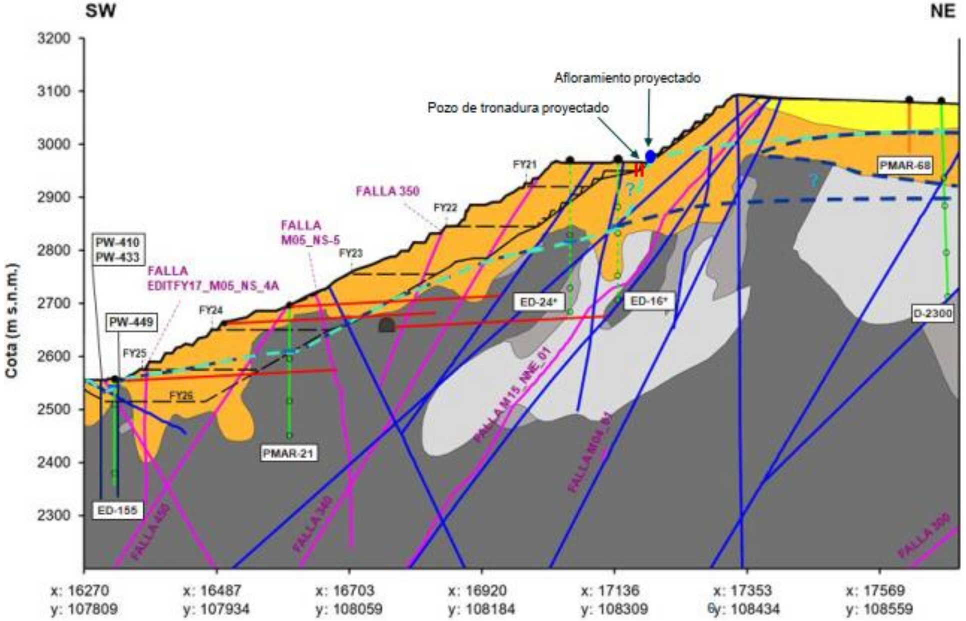


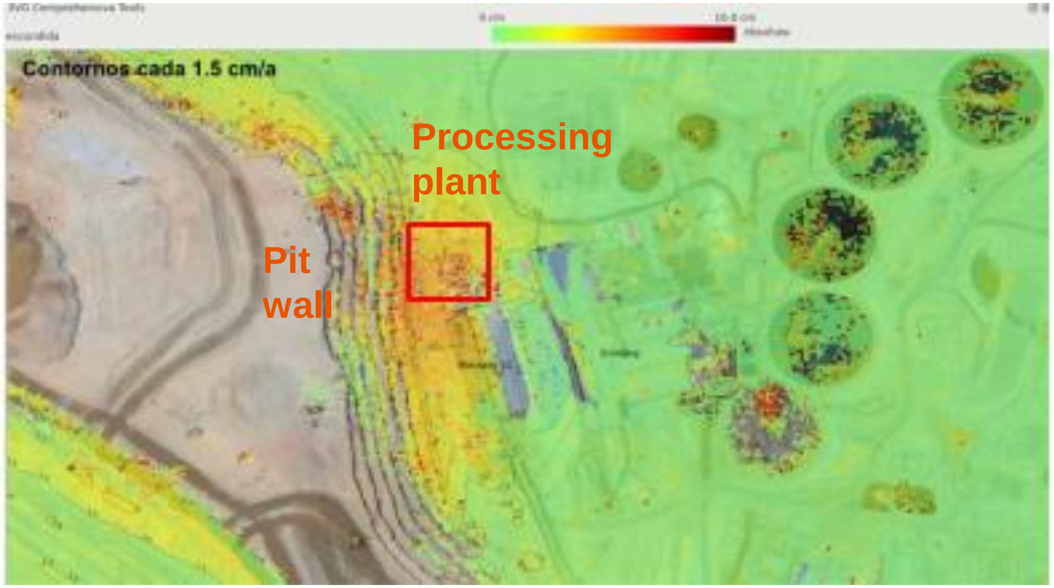
Additional assessments

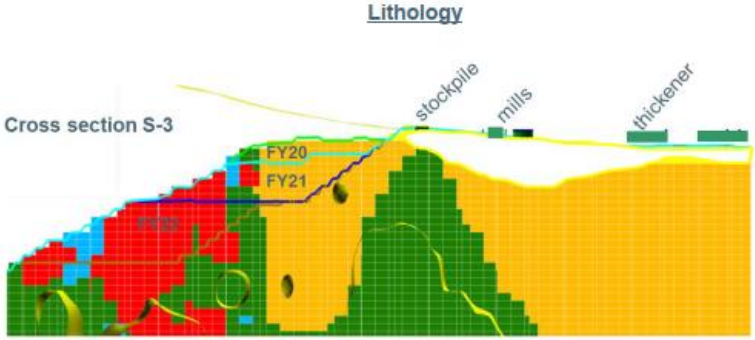
Pit wall interaction with mine infrastructure

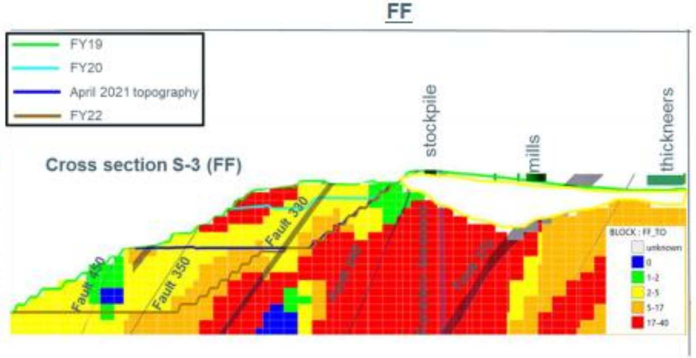
Master section









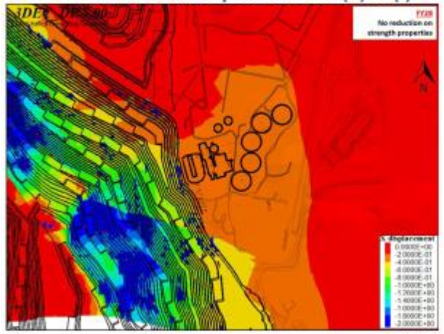


BHP

Additional assessments

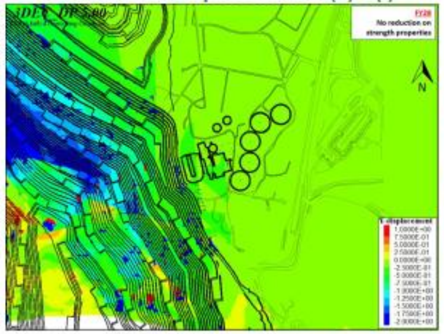
Pit wall interaction with mine infrastructure

Horizontal Displacement E(+)-W(-)



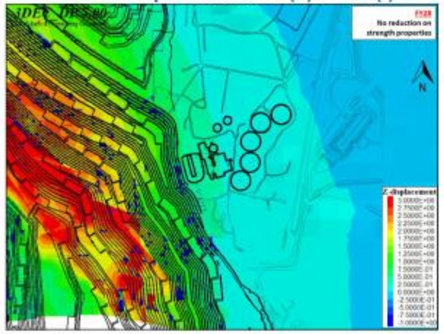
* Displacement up to 20 cm in FY27

Horizontal Displacement N(+)-S(-)

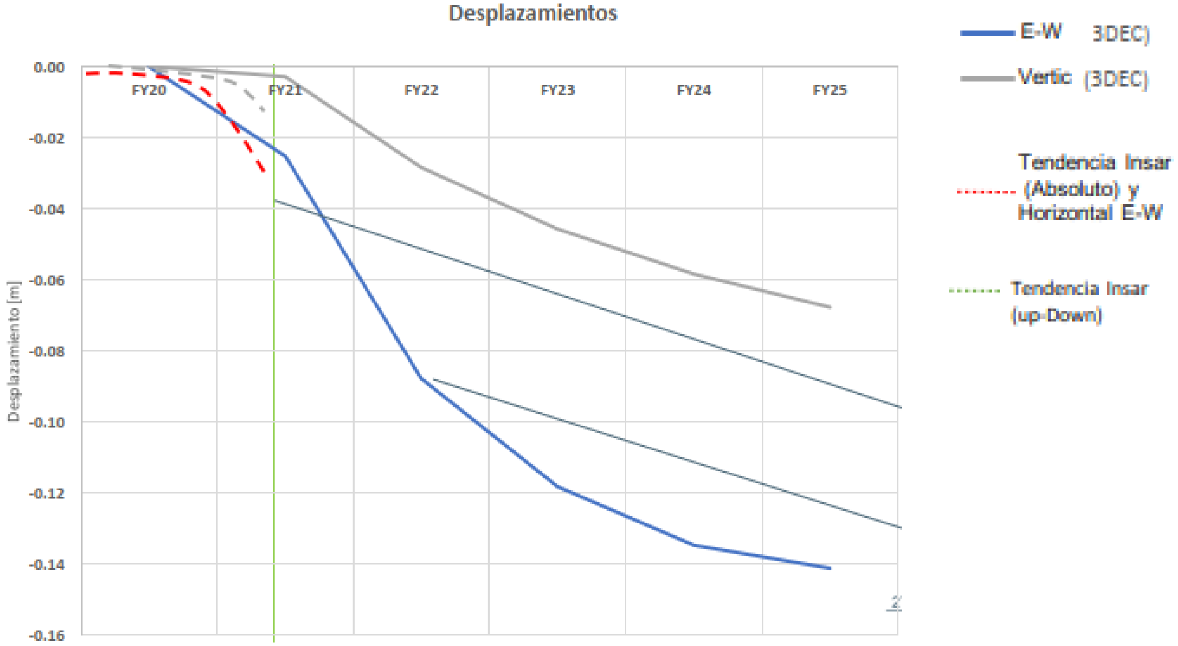


Displacemente up to 25 cm al FY27

Vertical Displacement UP(+)-Down(-)



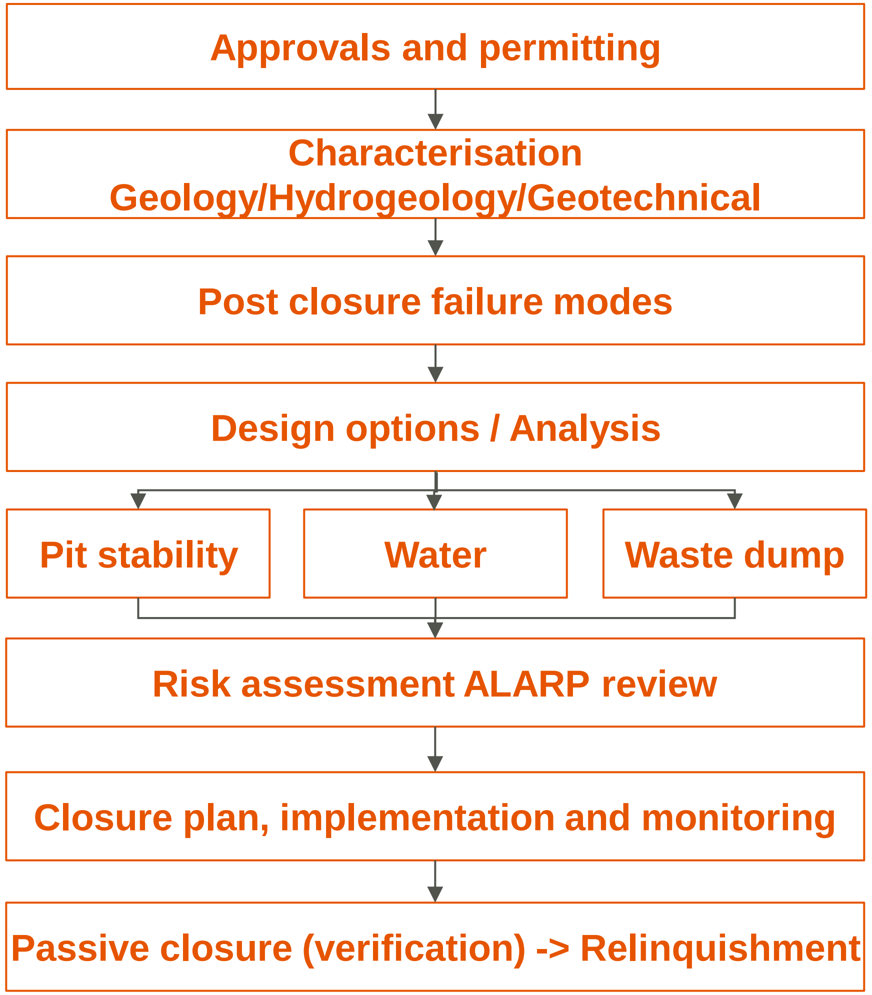
* Rebound effect issue.



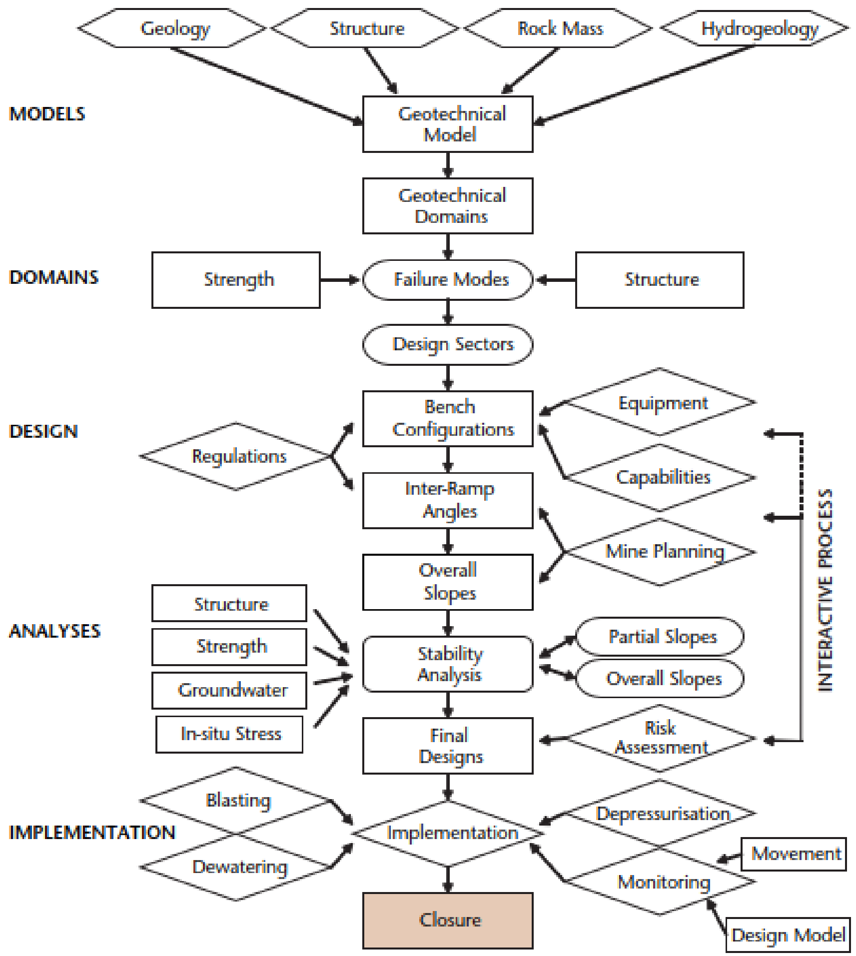
Additional assessments

Ground support

Mine closure considerations



LOP, 2024

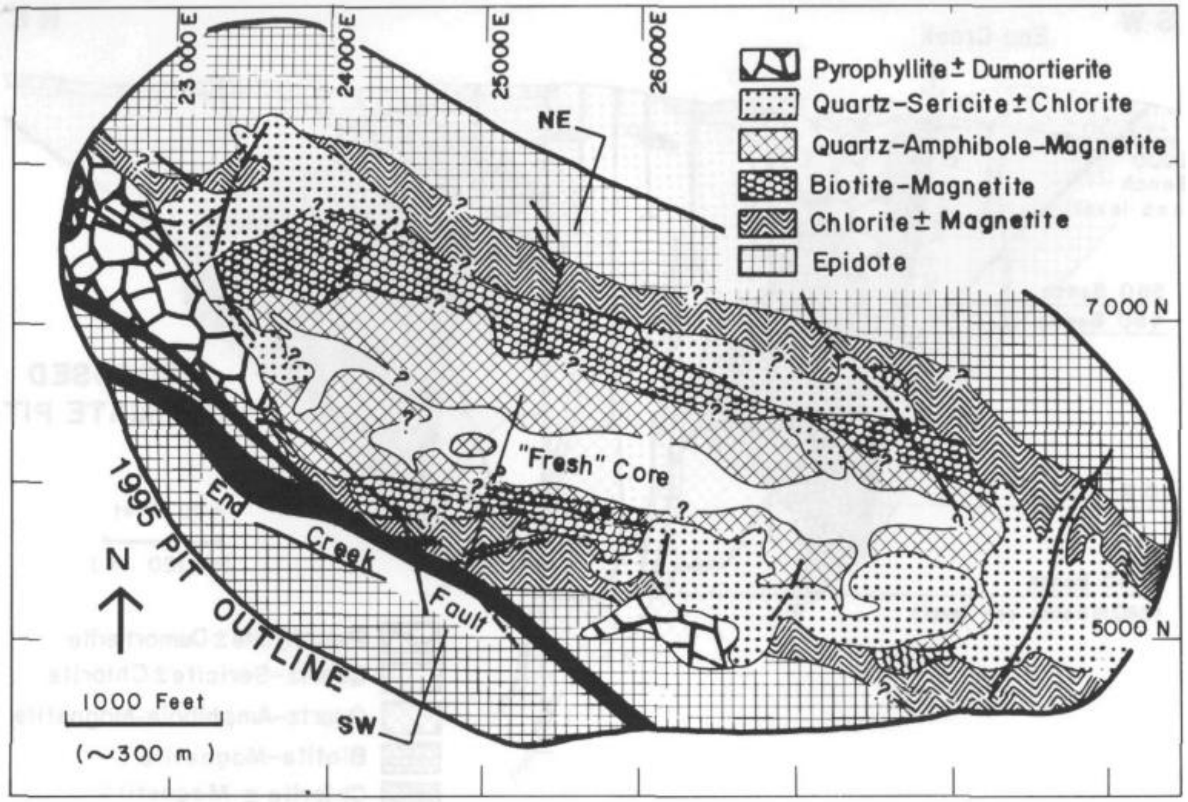


LOP, 2009

Mine closure considerations

Pit stability after mine closure

Pit lake formed after mine closure at BHP Island Copper mine



Geology at BHP Island Copper mine

BHP

Mine closure considerations

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FÍSICAS Y MATEMÁTICAS
UNIVERSIDAD DE CHILE

Failure modes

North east toppling

North wall slide

Mine closure considerations

Failure modes

West slope movement (north end)

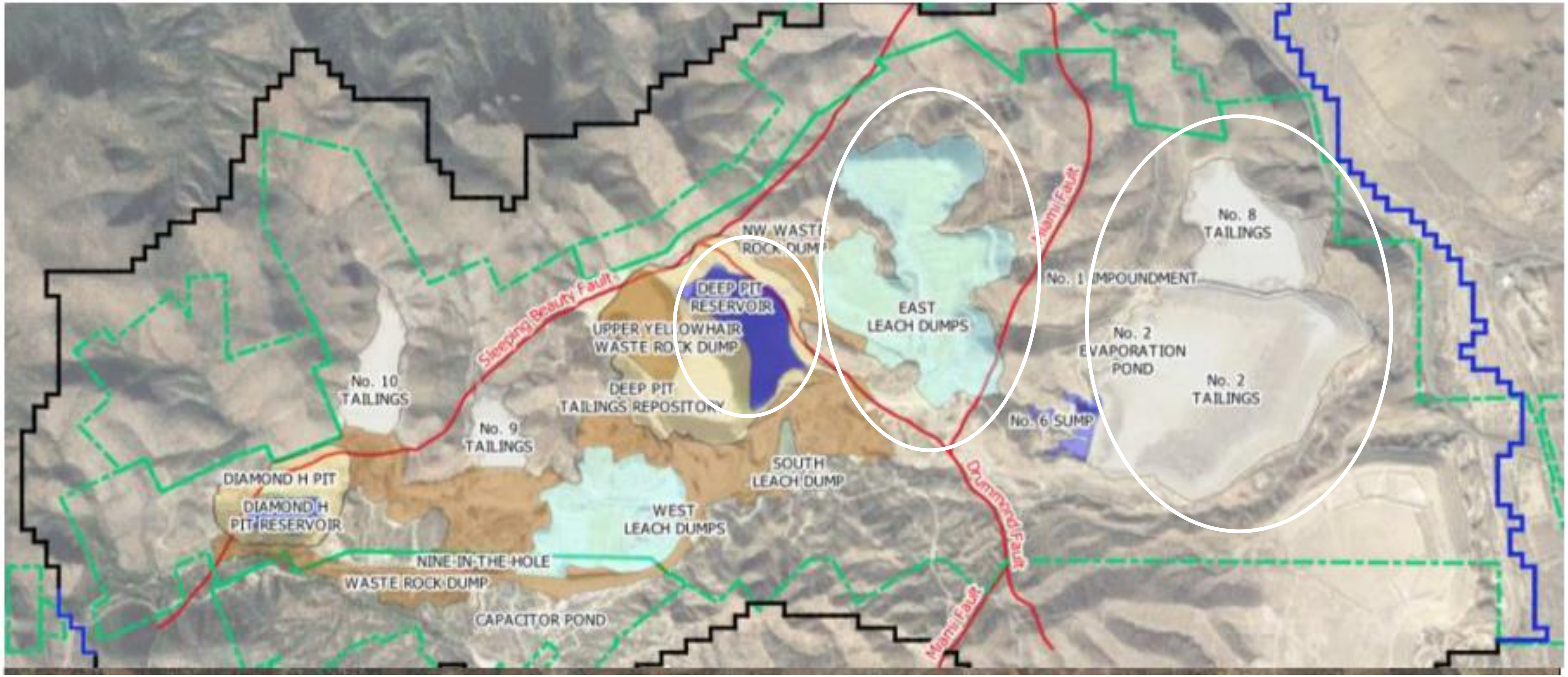
West slope movement (south end)

Mine closure considerations

Design options

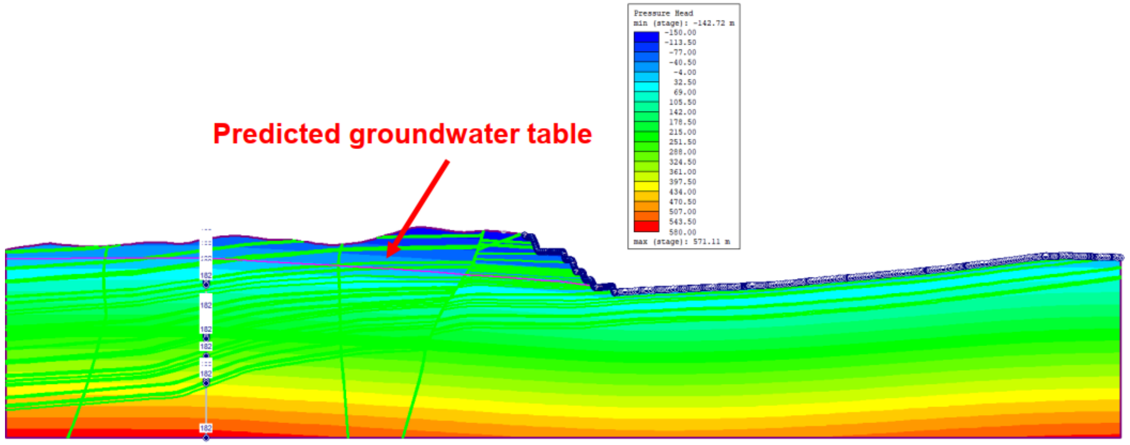
Mine closure considerations

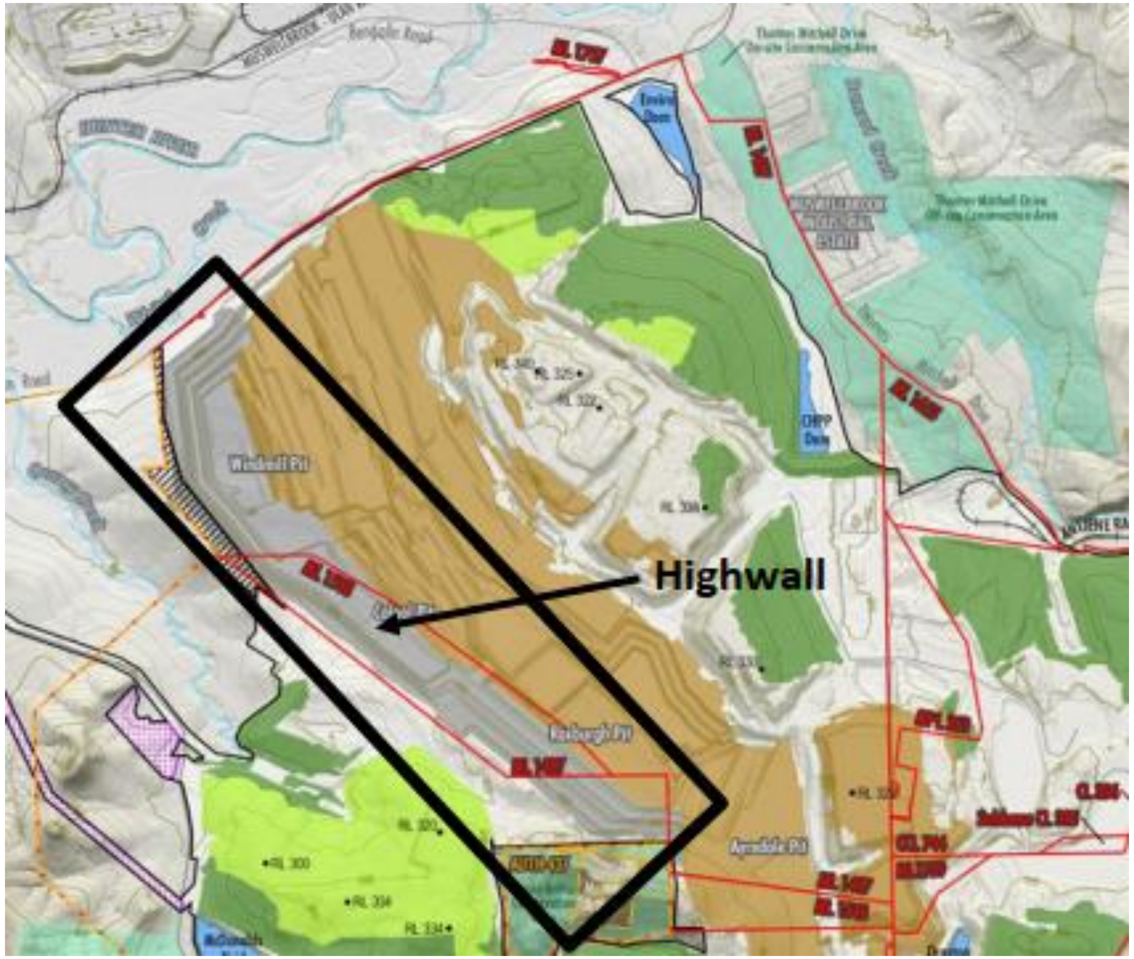
Design options



Mine closure considerations

Pit stability and water

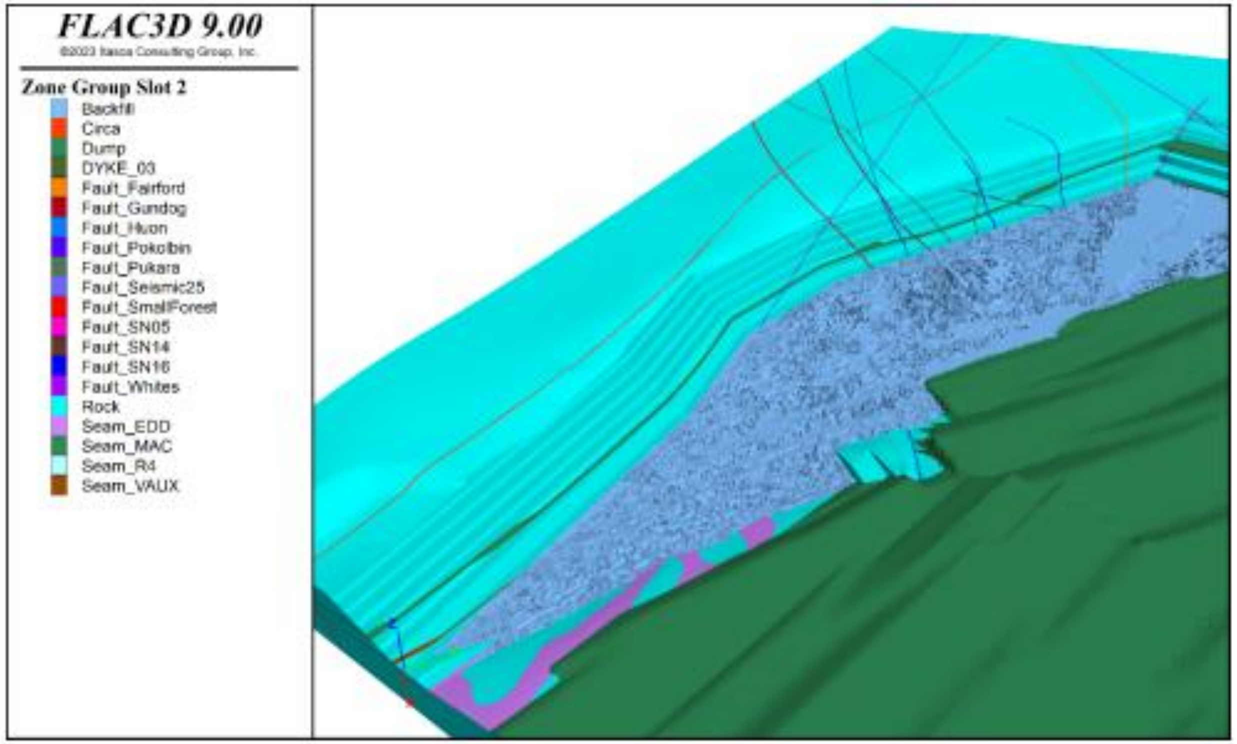




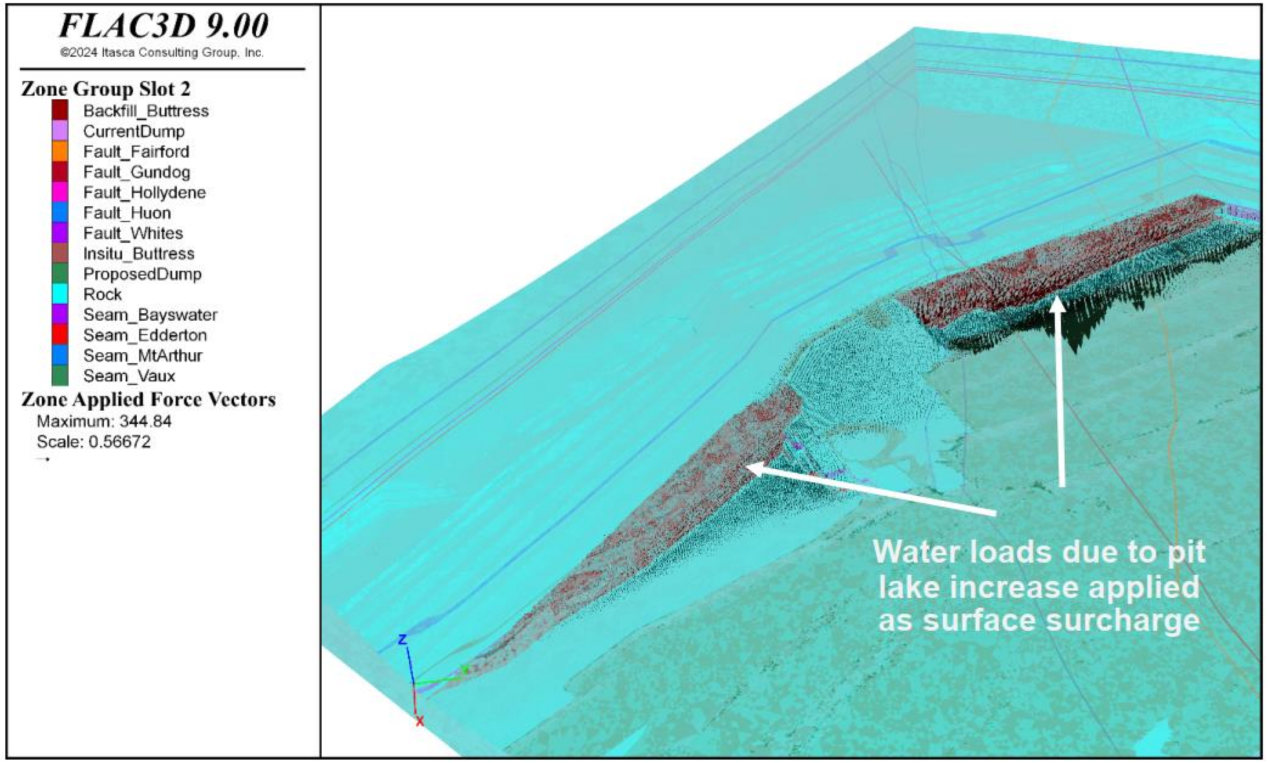
Mine closure considerations

Pit stability and water

Stability conditions after closure would include additional support (eg, buttress) and change of rockmass conditions (eg, pit lake formation)

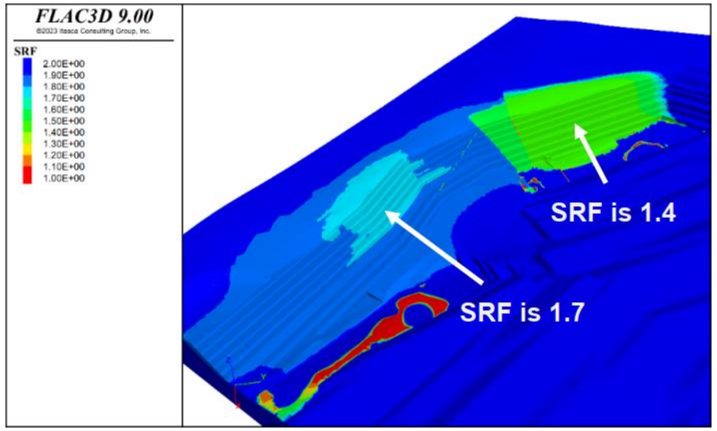


(b) Run 3c - Backfill to RL0 m

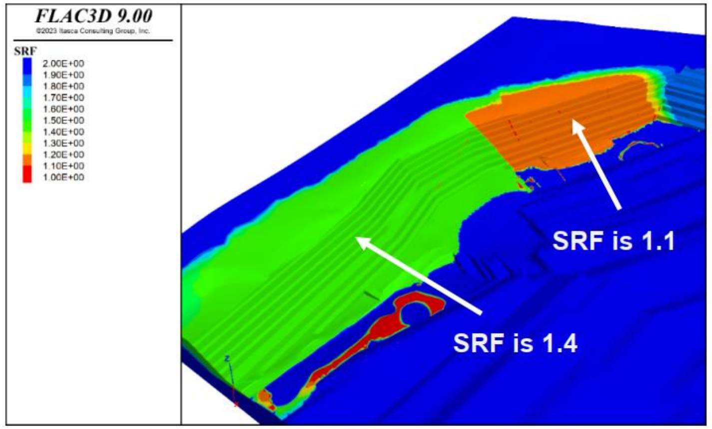


Mine closure considerations

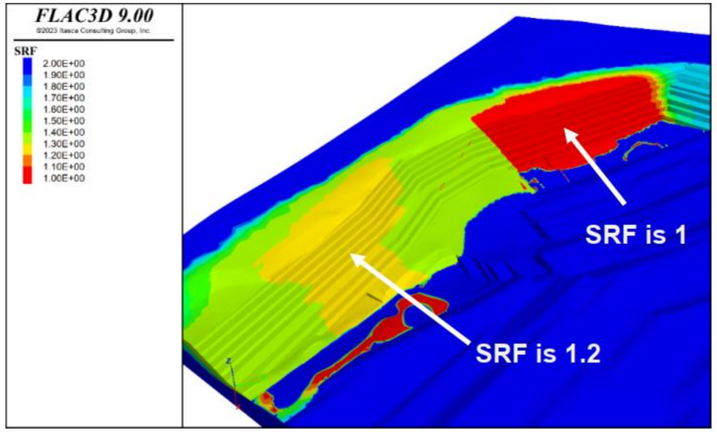
Pit stability and water



(a) Run 1 - Dry



(b) Run 1 - Wet (GWT 50m & Hu=0.7)



(c) Run 1 - Wet (GWT 30m & Hu=0.7)

Hu = pore pressure factor

QWT+ Groundwater table

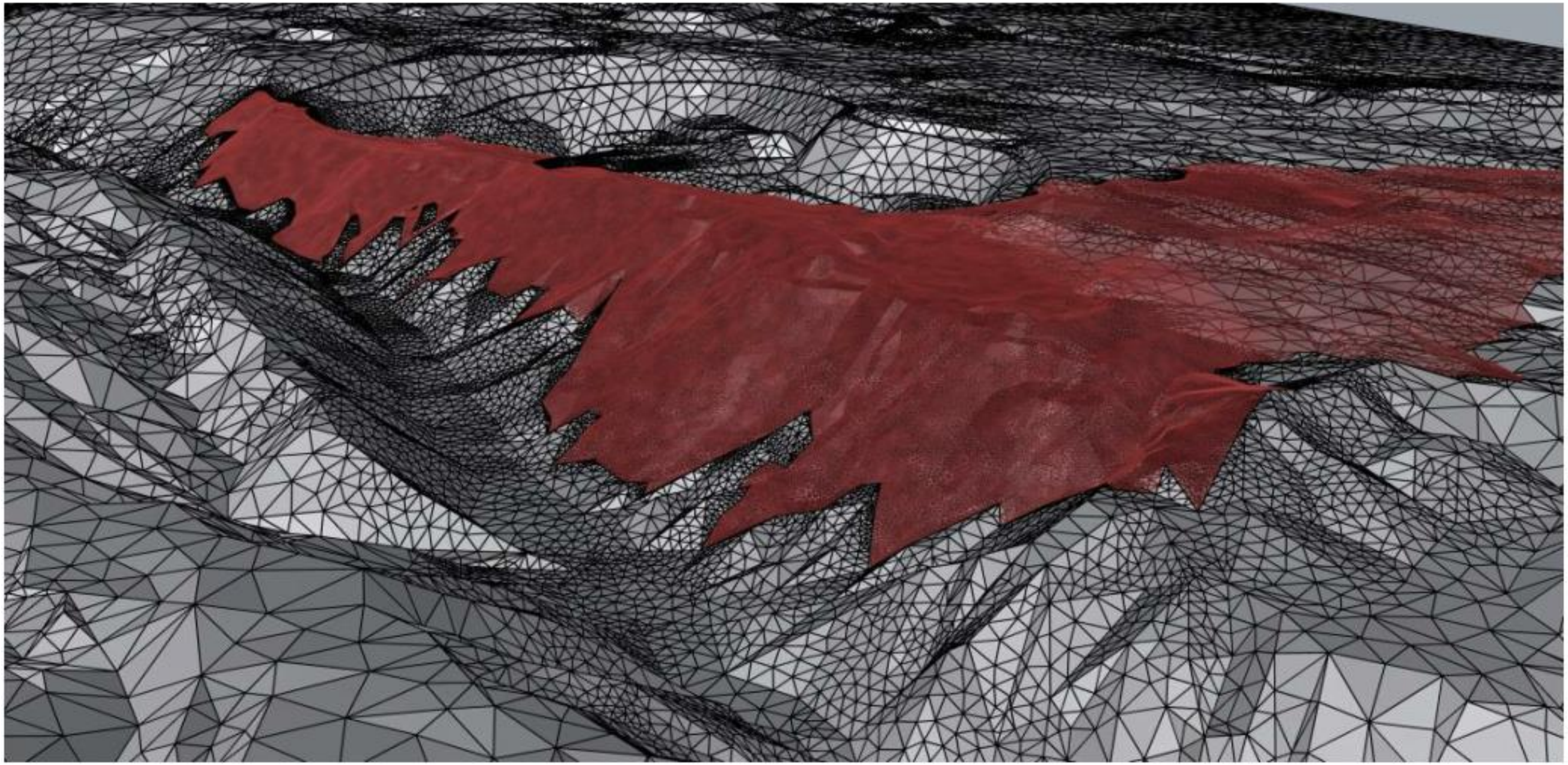
Mine closure considerations

Waste dump

BHP

Mine closure considerations

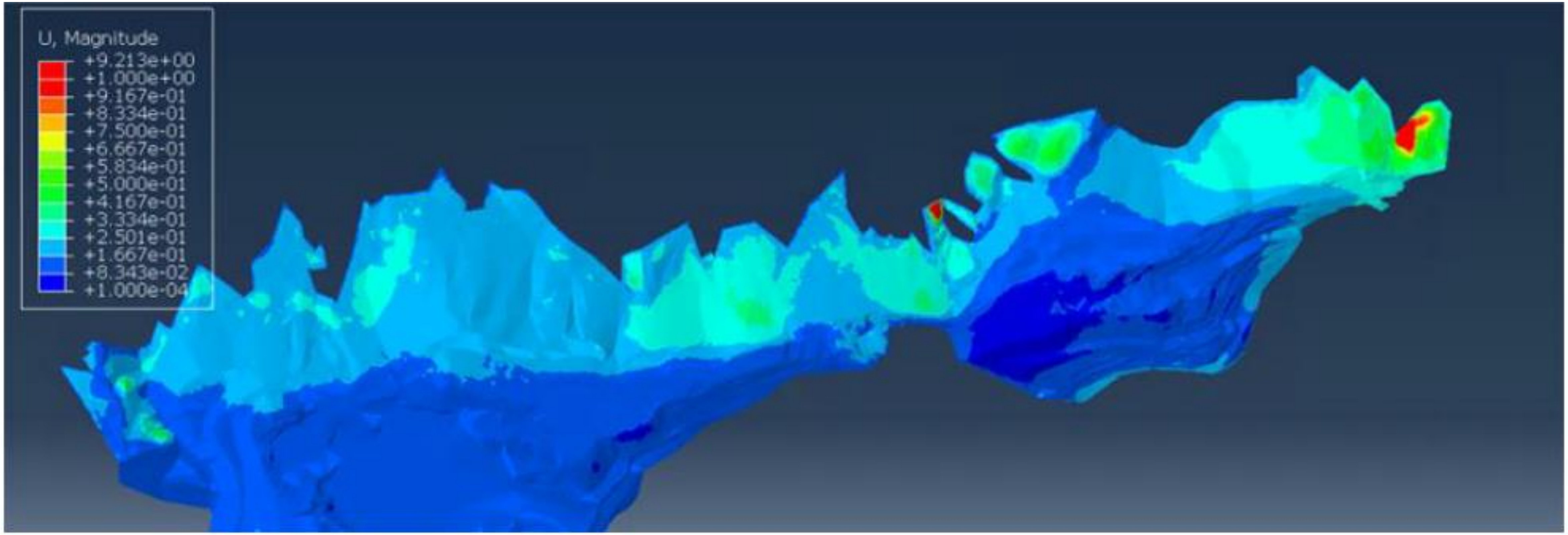
Waste dump



Mine closure considerations

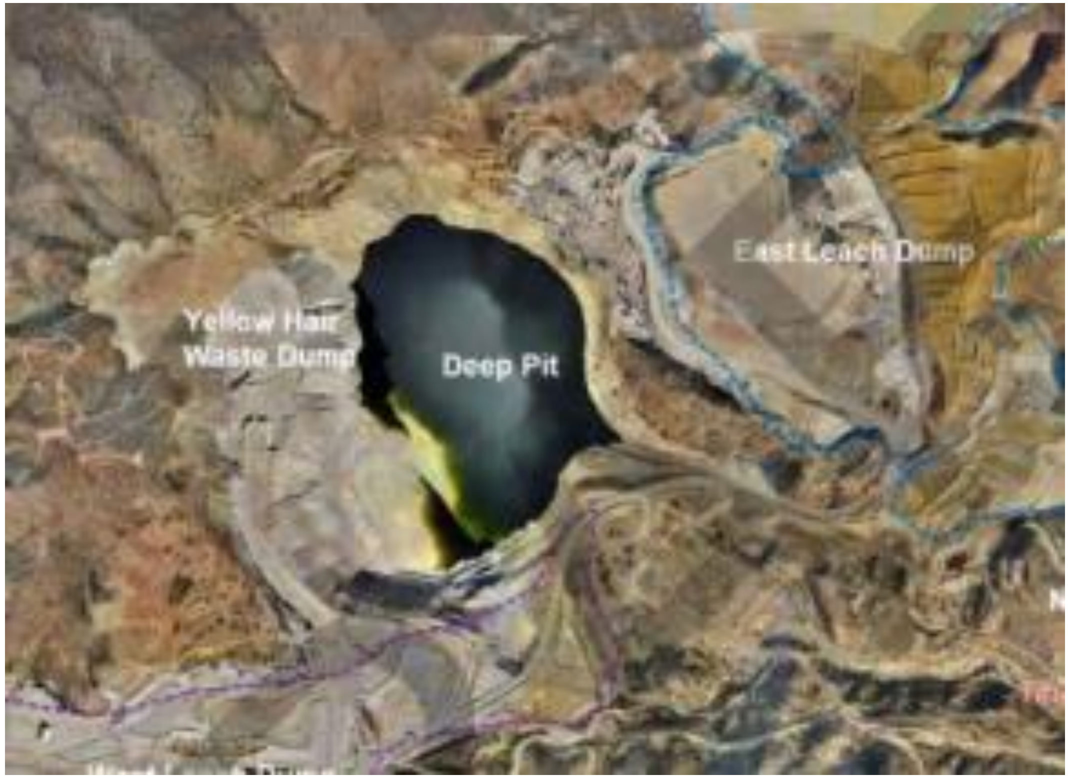
Waste dump

Waste dump after closure conditions may require modifications such as cutback some areas to meet stability conditions in the long term. Stability conditions after closure includes consequences on natural systems or local communities.



Mine closure considerations

Implementation and monitoring



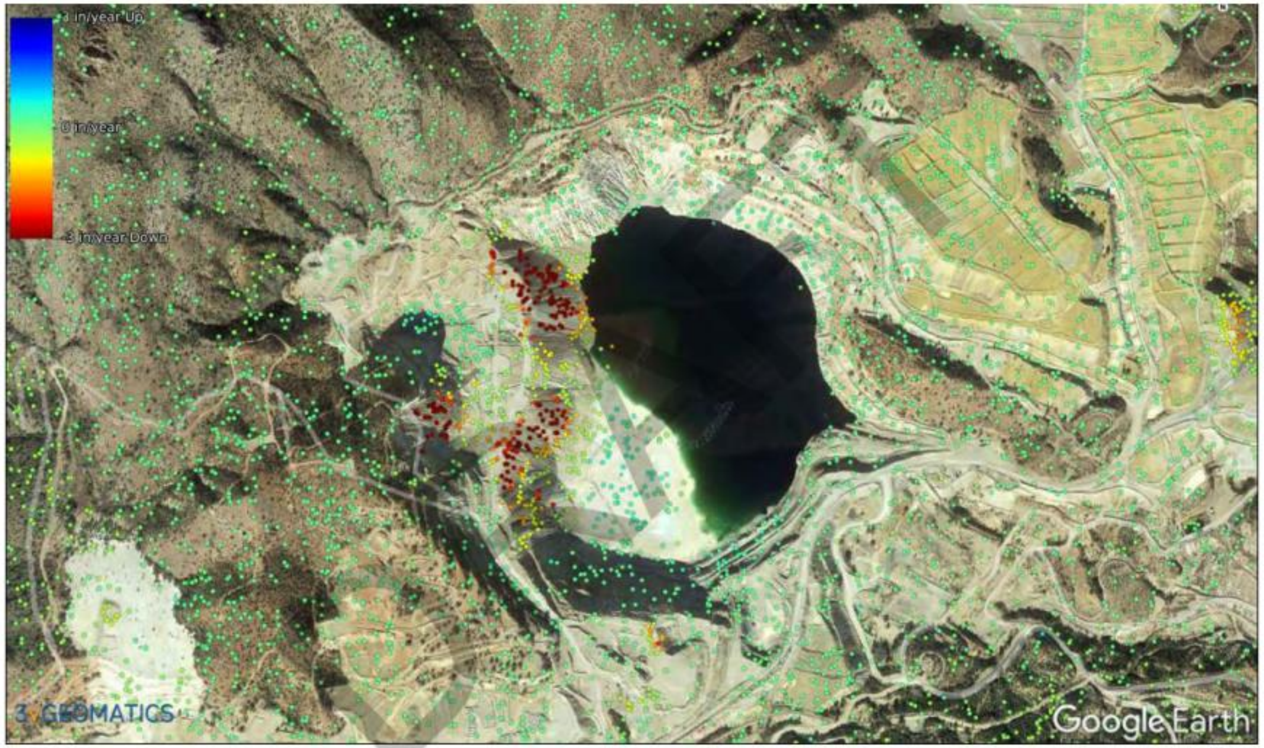
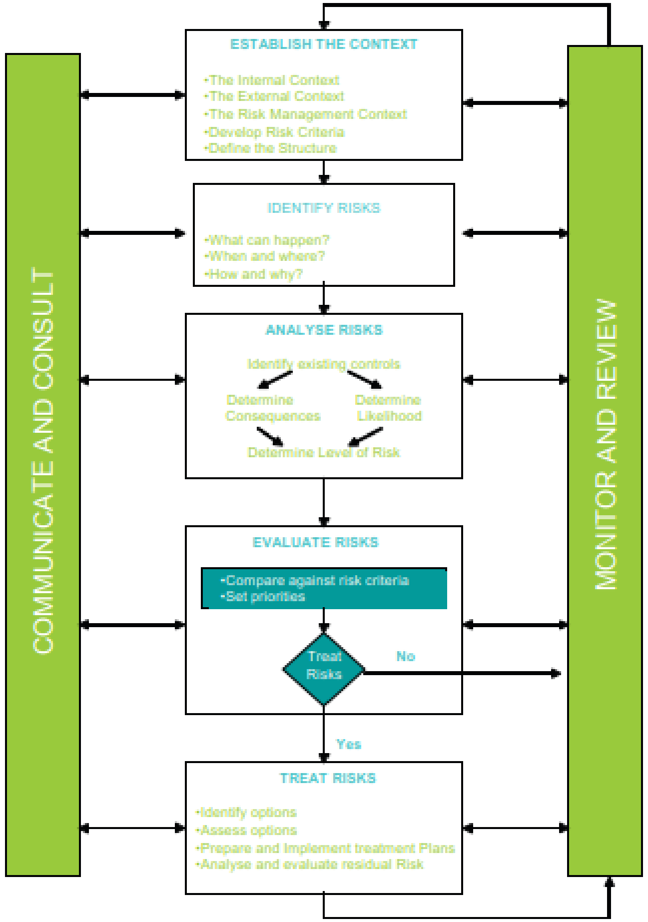


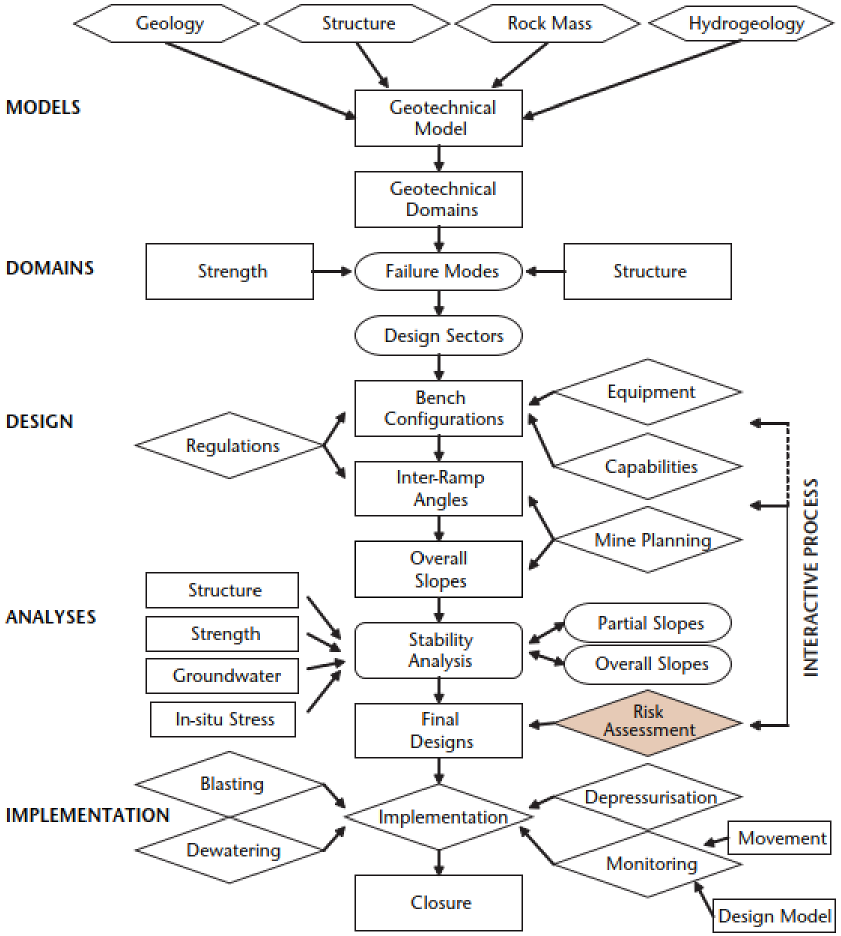
Figure 8.4: Deep Pit Detectable LOS Displacement Data Collected from the TerraSAR-X Satellite between June 2014 and March 2019

Risk management

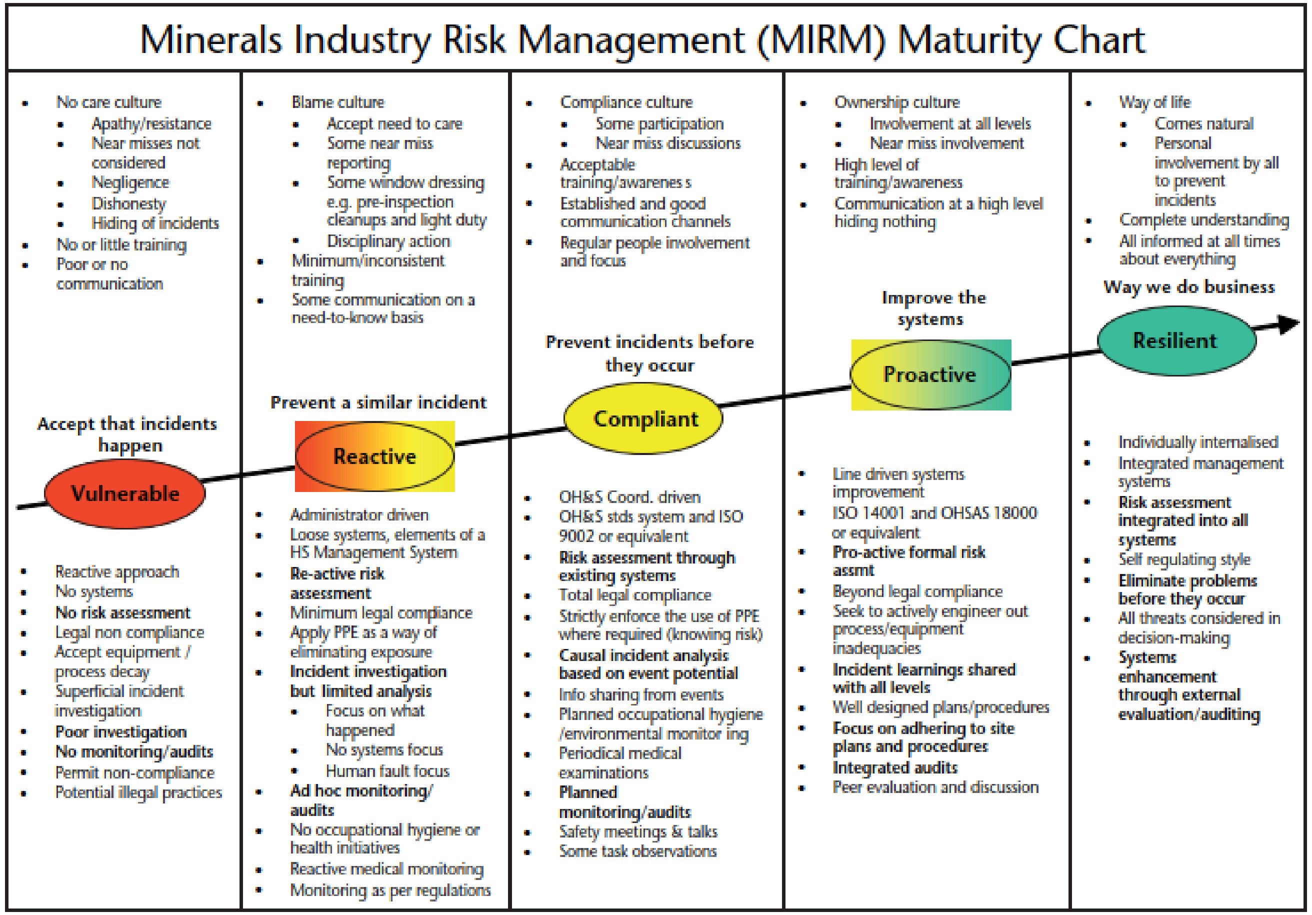
Flowchart

AS/NZ 4360:2004 RISK MANAGEMENT





Risk management



Risk management

Identify risks

Individual asset risks

- Fall of ground
- Stope failure
- Subsidence surface cave
- Etc

Risk assessment

Maximum foreseeable Loss (MFL), Likelihood and Residual Rick Rating (RRR)

Risk treatment

- Critical control execution (CCE)
- Critical control verification (CCV)
- Critical control observations (CCO)

Monitor and review

- Control Effectiveness Test (CET)
- Remediation plan
- Risk evaluation (RE)

Communicate and learn

Risk intelligence dashboard (portal)

Risk management

Bow tie

Implementation of design involves a risk management process and controls in place.

Geotechnical design is usually a critical control that requires other critical controls such as characterisation, monitoring and ground control for an effective implementation.

Sites	Example Scenarios for Sites	Potential causes	Preventive controls	Mitigating controls
	• Overall wall failure (height 240 m) • Overall wall failure (height 60 m) • Overall wall failure (height 550 - 600 m) • Overall wall failure (height 650 m) • Overall wall failure (height 340 m) • Overall wall failure (height m) • Overall wall failure (height 50 m) • Overall wall failure (height 500 m)	1. Adverse rock mass quality 2. Adverse structural systems 3. Excessive pore pressures 4. Adverse natural conditions (tectonic earthquakes, rainfalls or wind) 5. Poor geotechnical assessment 6. Deviation of design execution 7. Ineffective geotechnical monitoring (including piezos) 8. Ineffective ground control 9. Operational practices - Excessive design/execution of drill&blast (blast damage) or over digging	1. Geotechnical wall design 2. Surface Water / Groundwater management 3. Wet season preparedness plans 4. Geotechnical characterisation 5. QA/QC / as builts 7. Monitoring and response system b. Geotechnical reconciliation 8.Ground control system 9. Capability / QA/QC	1. Emergency response plan
	• Failure propagation to Rancheria river			
	• Failure creating tsunami at the bottom of pit lake			
	• Failure propagation to Peak Downs railway corridor • Failure propagation to Denman (public) road (Mt Arthur)			
	• Failure propagation to Los Colorados extension • Failure propagation to Hamburgo Tailings			

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