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

Rigo Rimmelin

BSc (Mining Eng), MSc (Geotech Eng), FAusIMM

02 Octubre 2024

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

Auspiciador

GEOBRUGG®

BRUGG

Safety is our nature

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

Table of contents

Introduction

Stability analysis

Compliance with a stability acceptance criteria

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

Scale of analysis

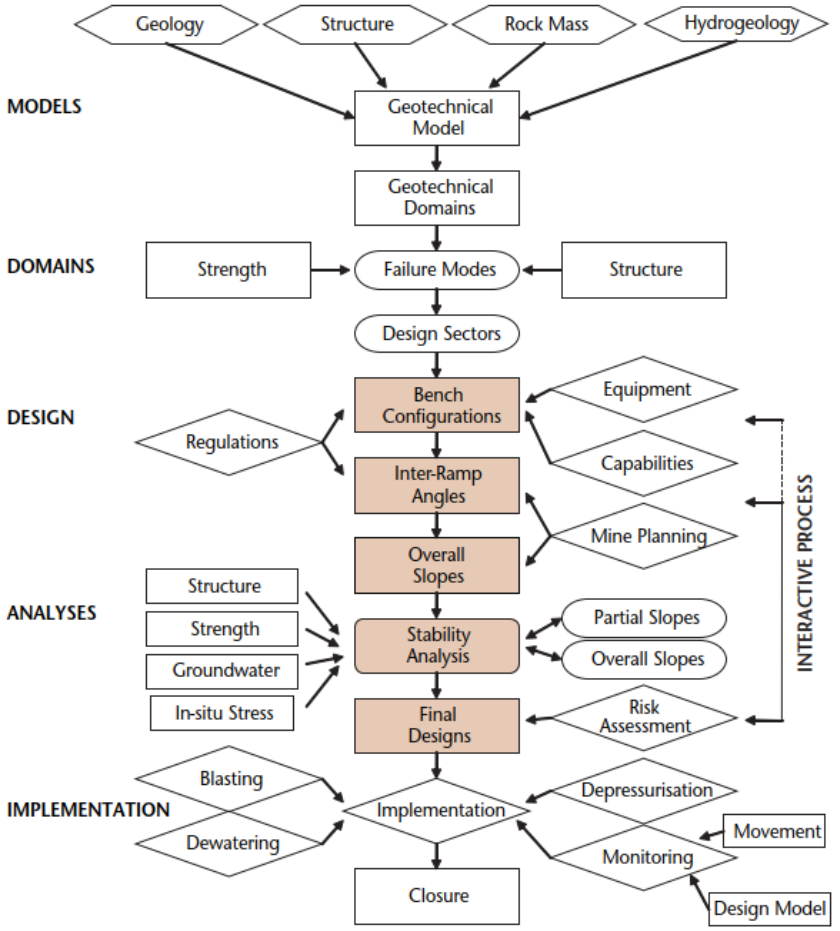
- Bench configuration
- Interramp slope
- Global slope

Techniques

- Limit equilibrium
- Numerical modelling

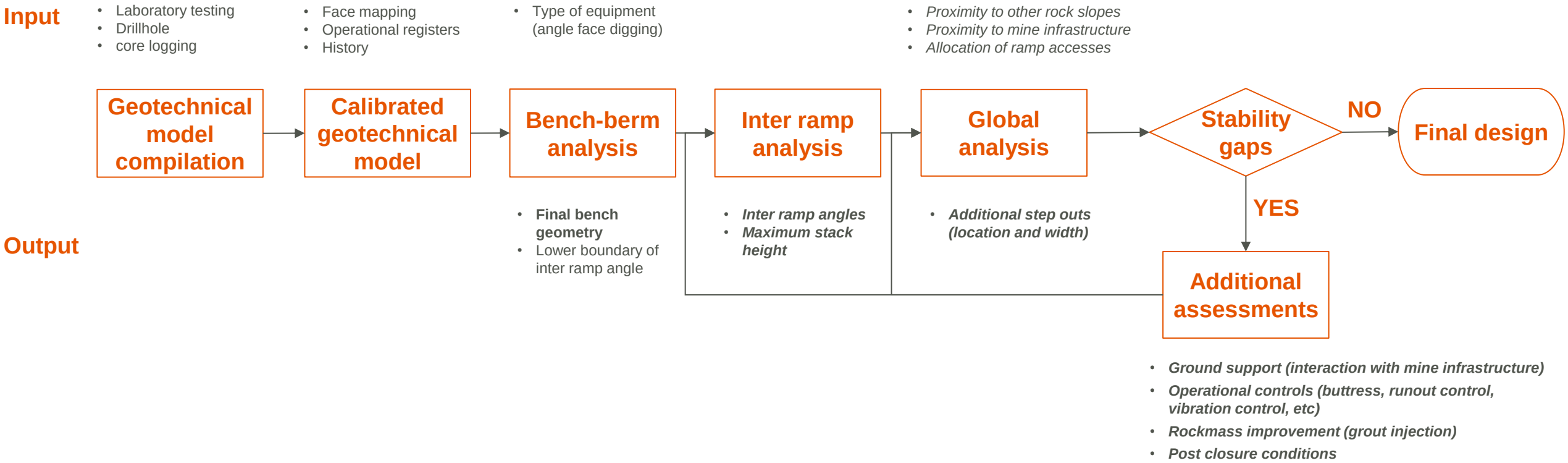
Outcome

- Final design -> slope geometry



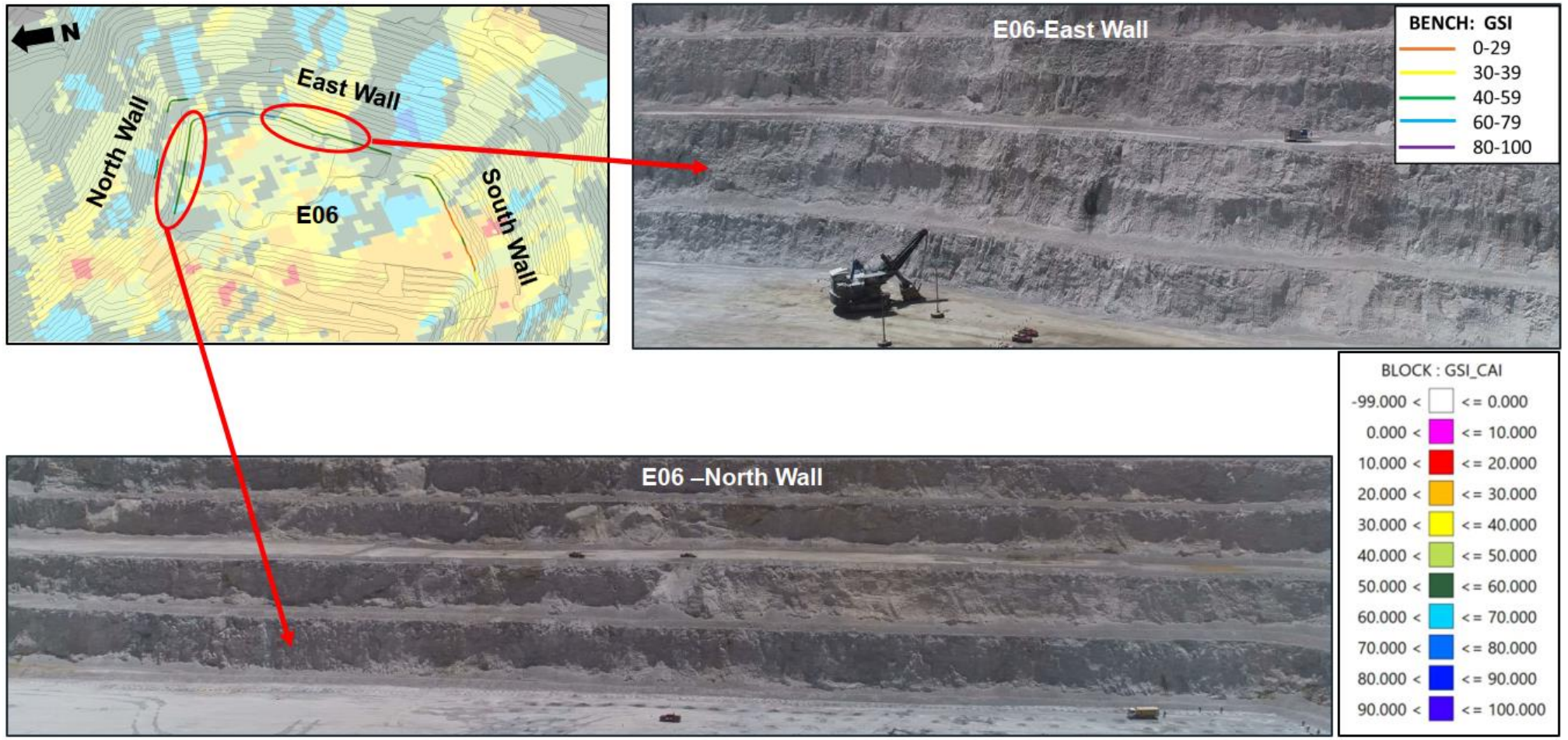
Introduction

Mining slope design process



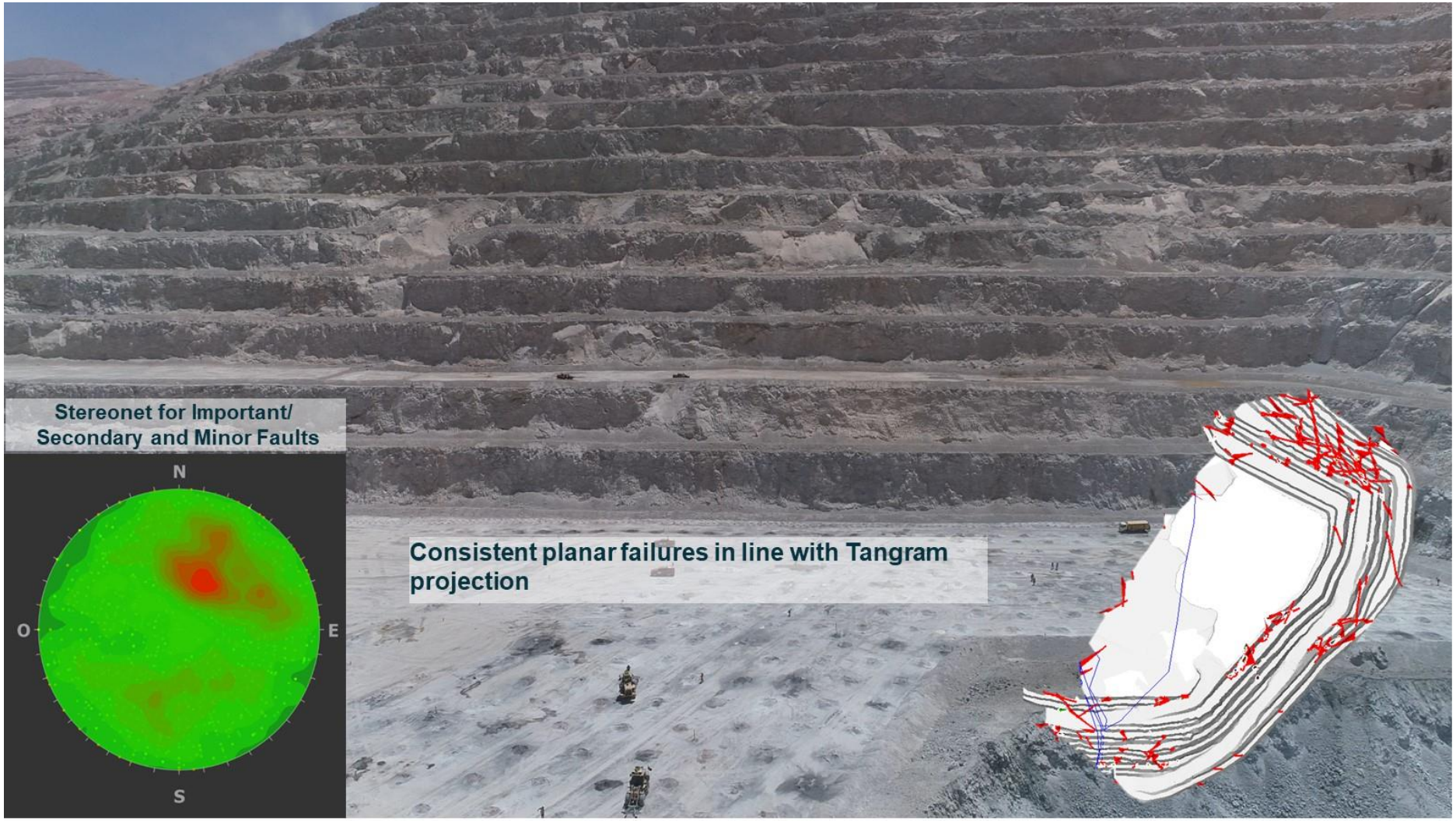
Calibration of geotechnical models

Models vs reality (rockmass classification)



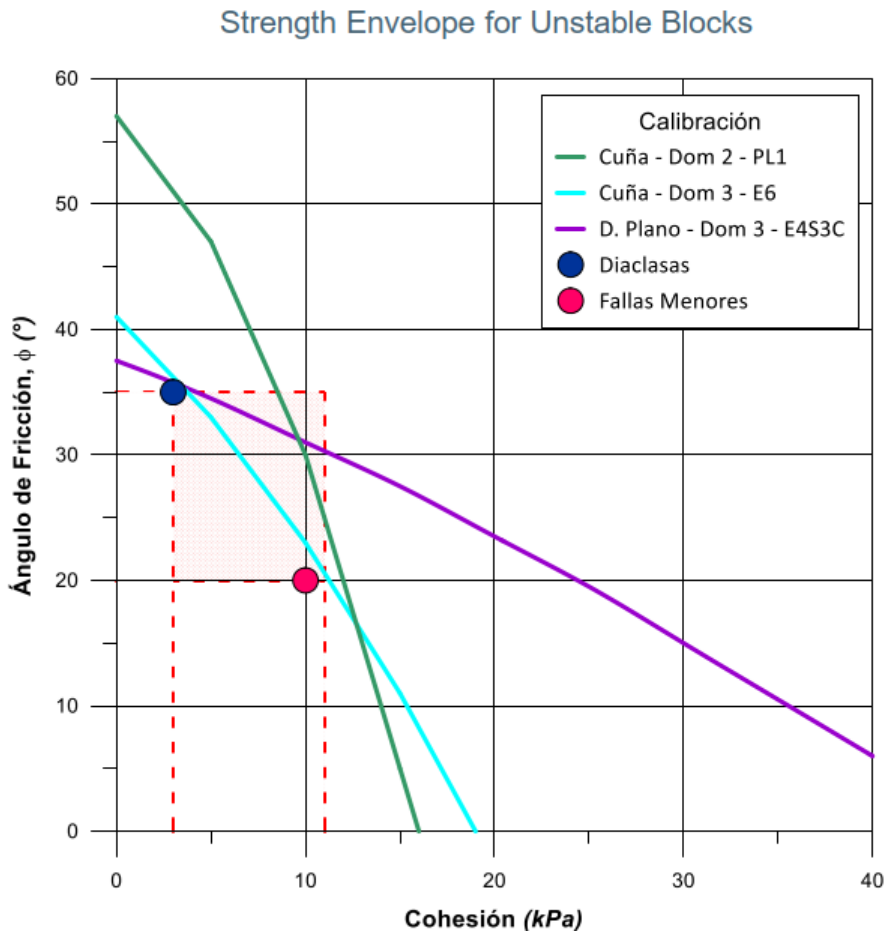
Calibration of geotechnical models

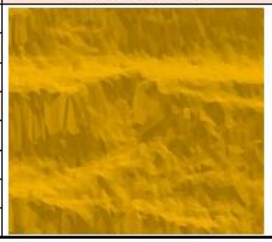
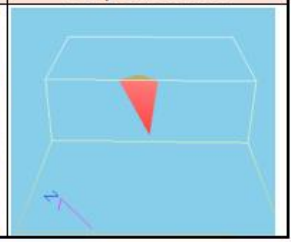
Model vs reality (structural condition)

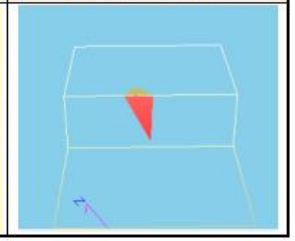


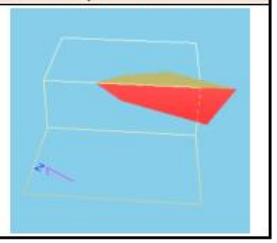
Calibration of properties

Backanalysis



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

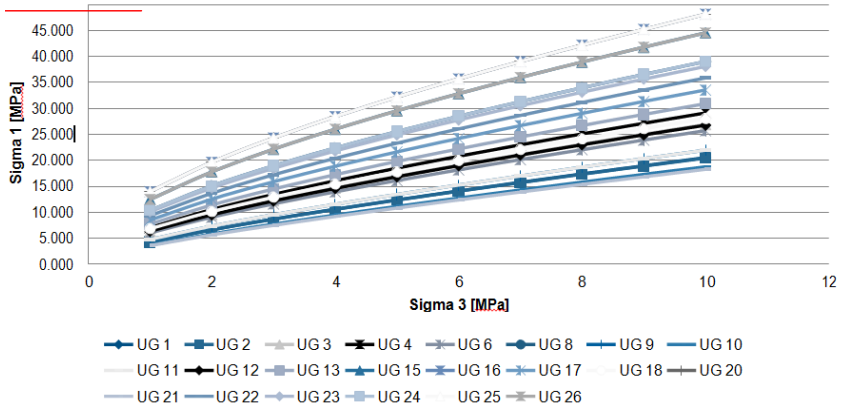
Geometría del Talud			Sector E6	
Dominio 3	h_b (m)	B (m)	Condición Actual	Bloque modelado
	15	13		
	Dip (°)	Dipdir (°)		
	65	221		
Estructuras				
Set	Dip (°)	Dipdir (°)		
1	69	262		
2	53	165		
3	-	-		

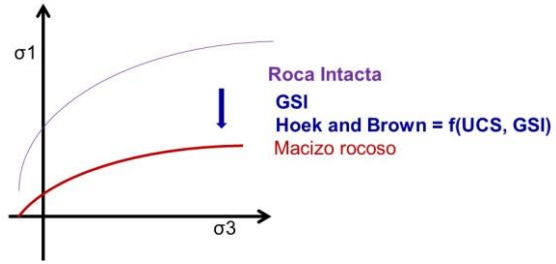
Geometría del Talud			Sector E4S3C	
Dominio 3	h_b (m)	B (m)	Condición Actual	Bloque modelado
	15	12		
	Dip (°)	Dipdir (°)		
	65	245		
Estructuras				
Set	Dip (°)	Dipdir (°)		
1	38	234		
2	40	217		
3	56	264		

Calibration of properties

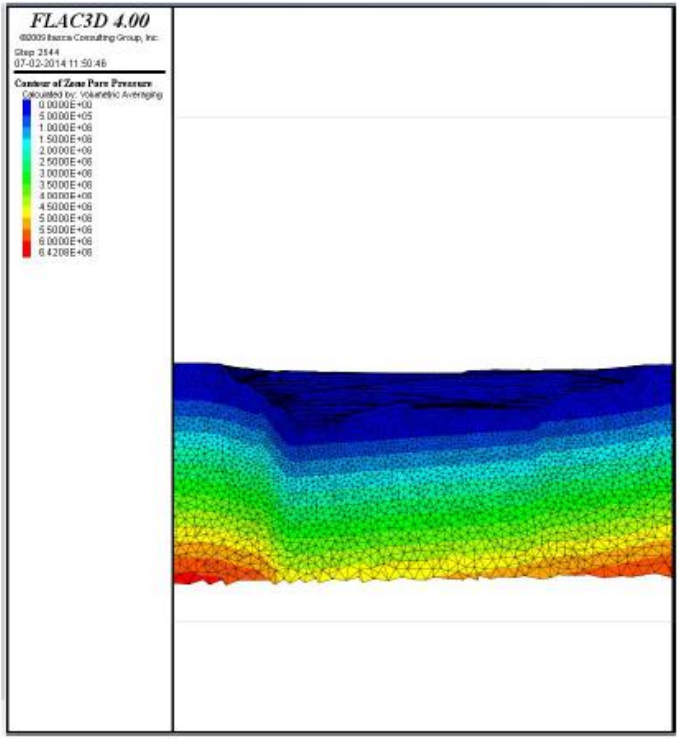
Geotechnical units and mechanical properties

Failure envelopes



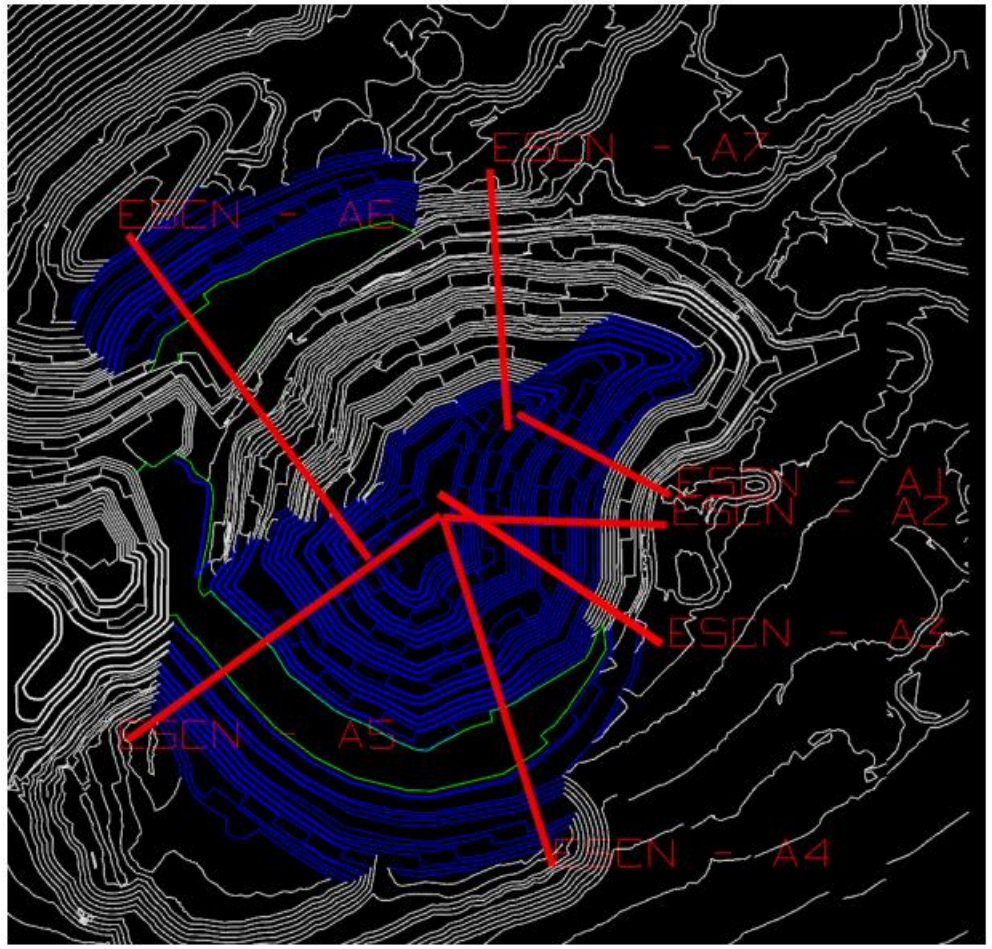


Pore pressures

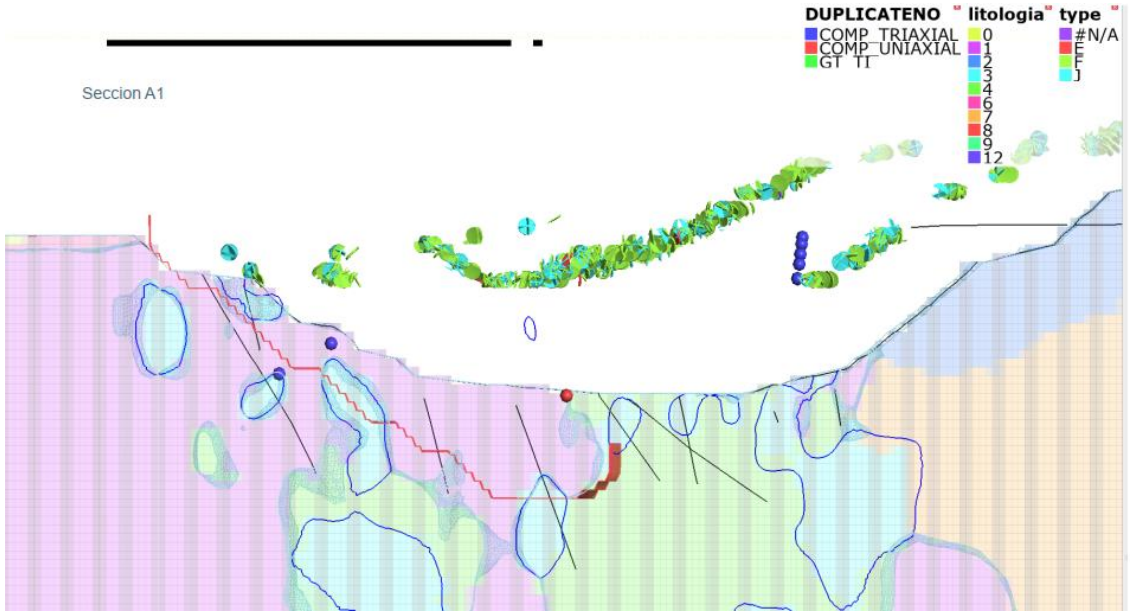


Calibration of geotechnical models

Master sections

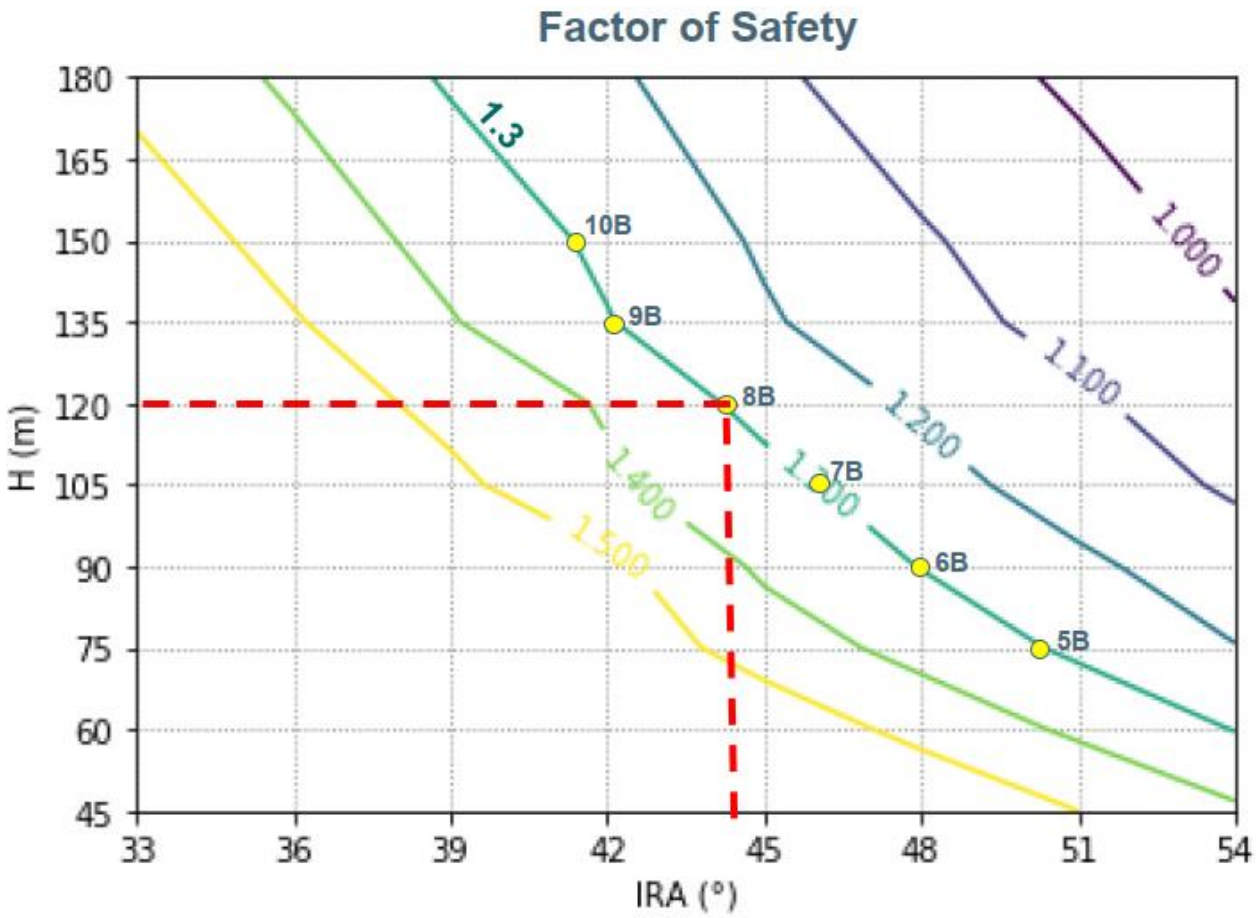


- Visualisation of all available data and reconciliation of reality vs models
- Representative of expansions (mine sequence) in terms of orientation, geotechnical units, structural conditions and ground water.

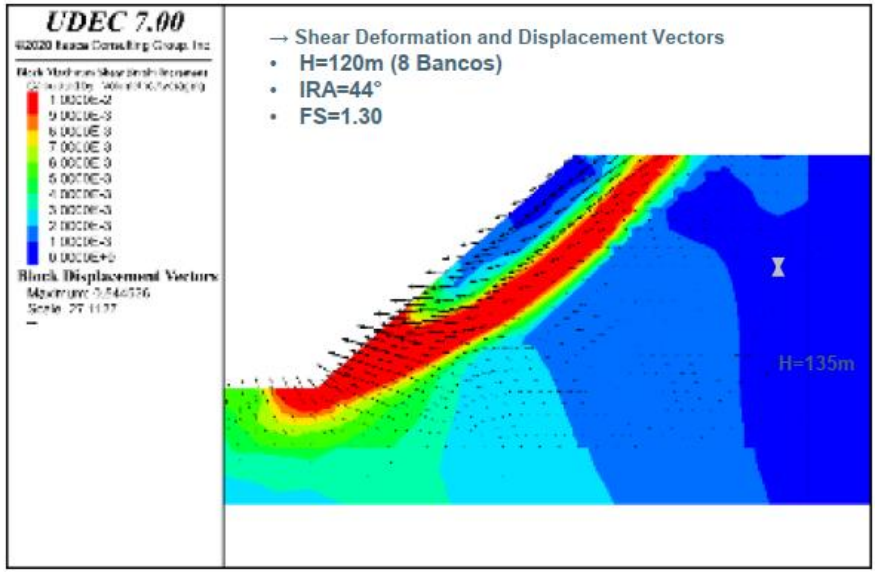


Inter ramp analysis

Design curves

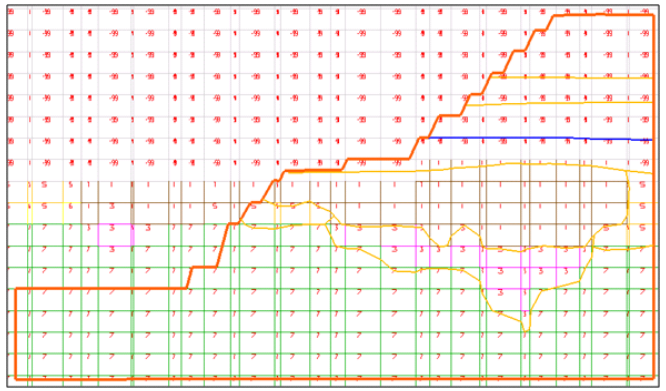


Porphyry Feldspar		
Parameter	Value	Observation
GSI	25	Representative value
UCS	28 MPa	Estimated value based on PLT
Mi	9	Estimated value
D	0.5	Damage conditions

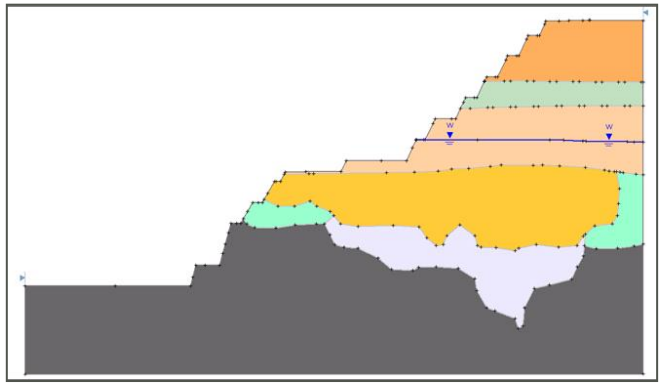


2D Global analysis

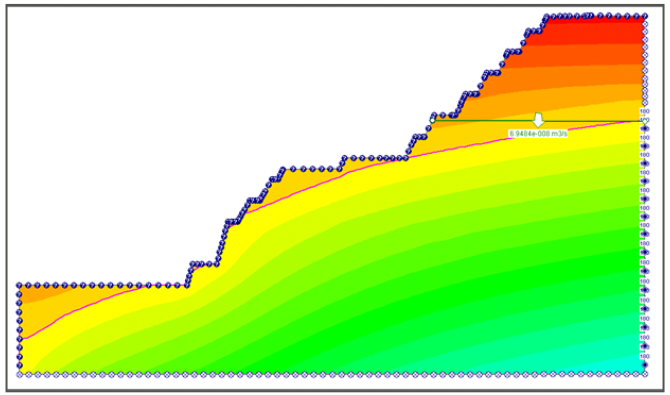
Building blocks



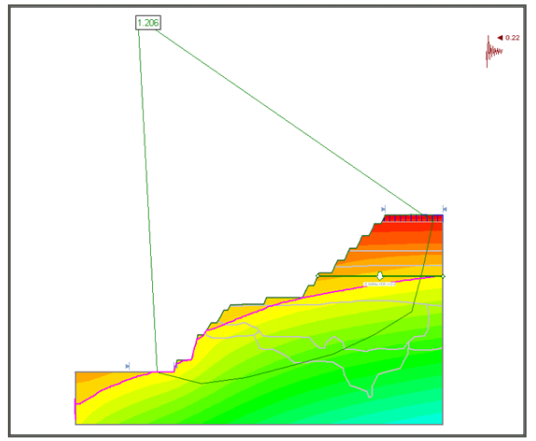
Geotechnical units (block model)



Geotecnical section (geotechnical unit + piezometric line)



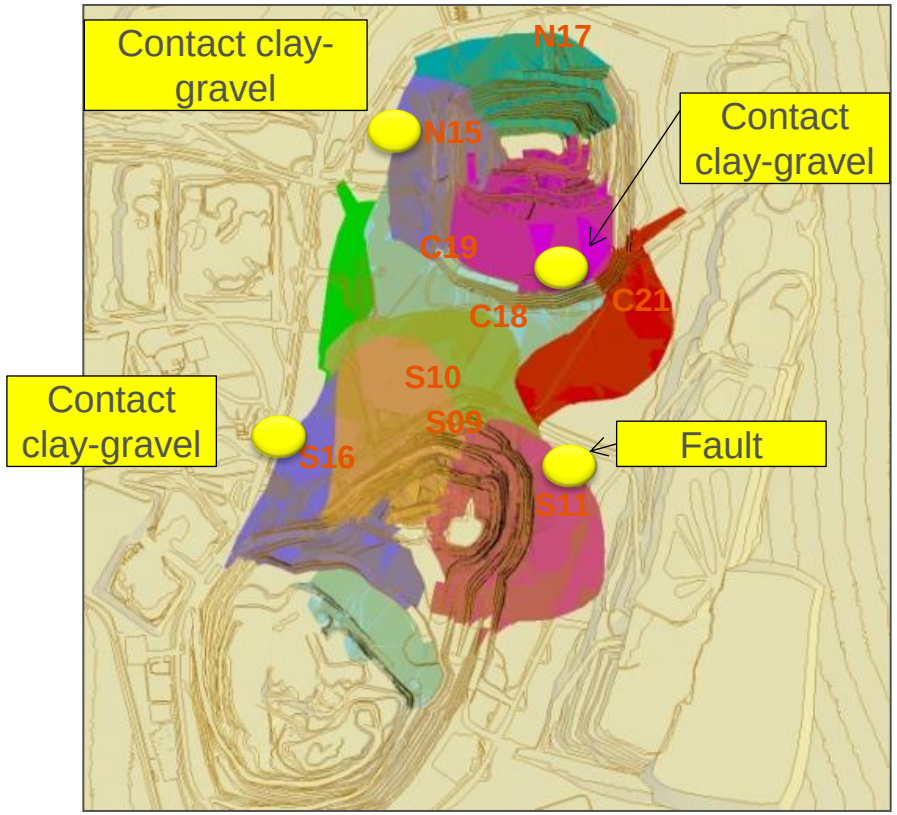
Numerical estimation of pore pressures



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

2D Global analysis

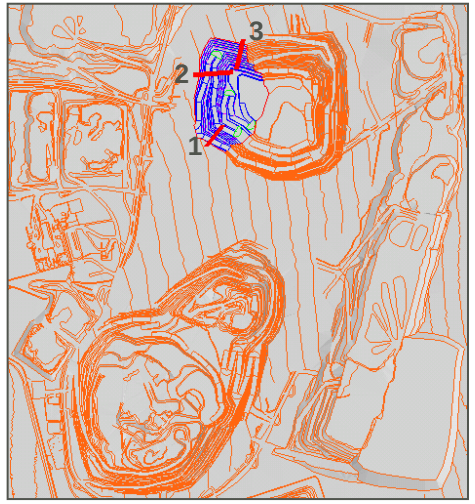
Mine sequence



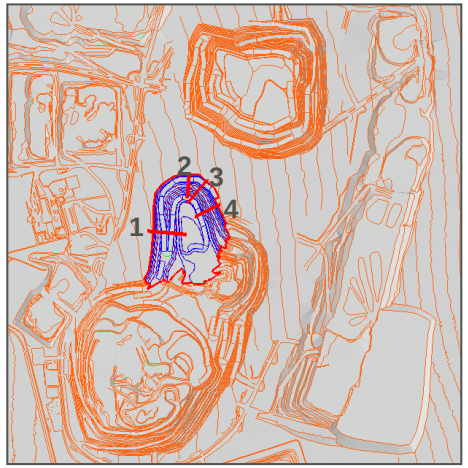
Casos		Factor de Seguridad	
		Probabilidad de Falla	FS
Estático	S09	0,6%	2,24
	N14	0,1%	2,29
	N15	20,9%	1,30
	S10	8,3%	1,62
	S16	4,3%	1,85
	S11	1,8%	1,60
	C18	1,2%	1,76
	C19	6,4%	1,56
	N17	11,7%	1,53
	C20	2,8%	1,94
	C21	4,6%	1,71
	FASE_13	0,1%	2,37
Sismo operacional	S09	1,3%	1,94
	N14	0,7%	1,90
	N15	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

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

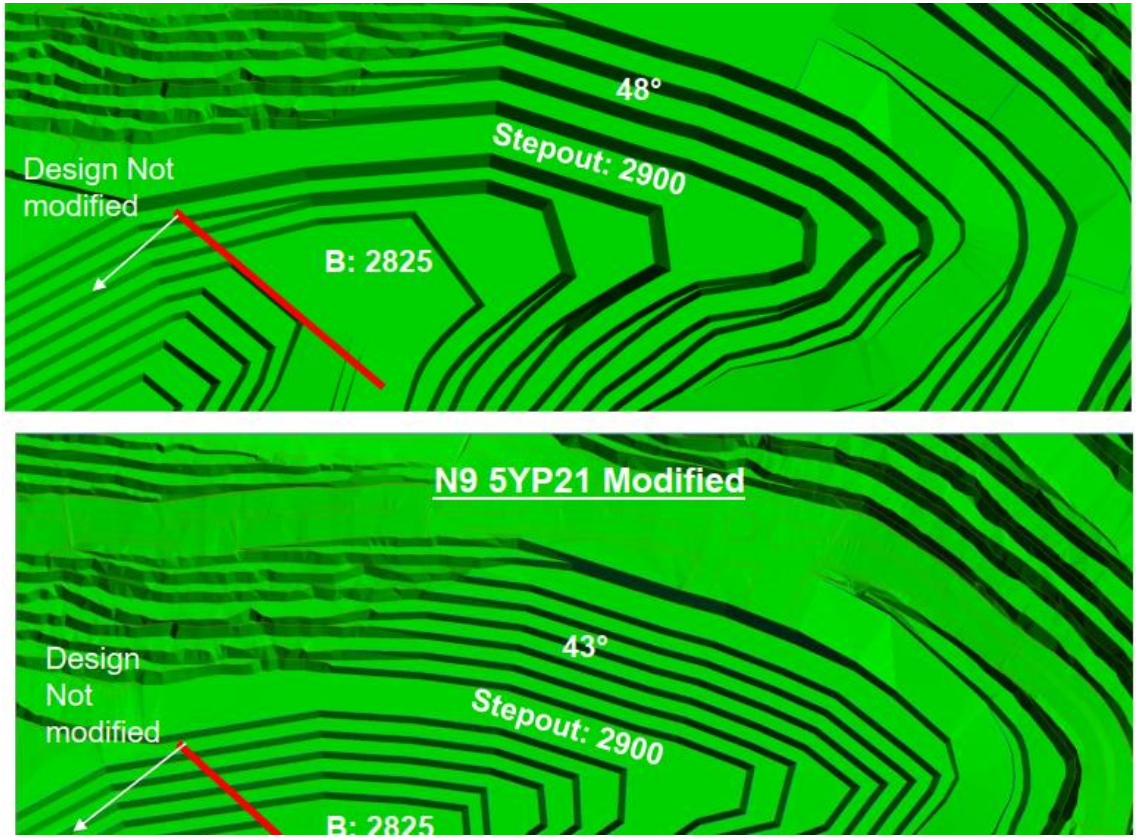


Fase	Perfil	Talud	Altura H (m)	Angulo (°)	Peso W (KN/m)	Estático Factor de Seguridad FS	Peso W (KN/m)	Sismo Operacional Factor de Seguridad FS	Peso W (KN/m)	Sismo Máximo Factor de Seguridad FS
S10	p01	Global	185	38	150	1,598	158	1,333	143	1,092
		Inter-Rampa	65	42	54	3,258	55	2,696	56	2,187
		Inter-Rampa	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

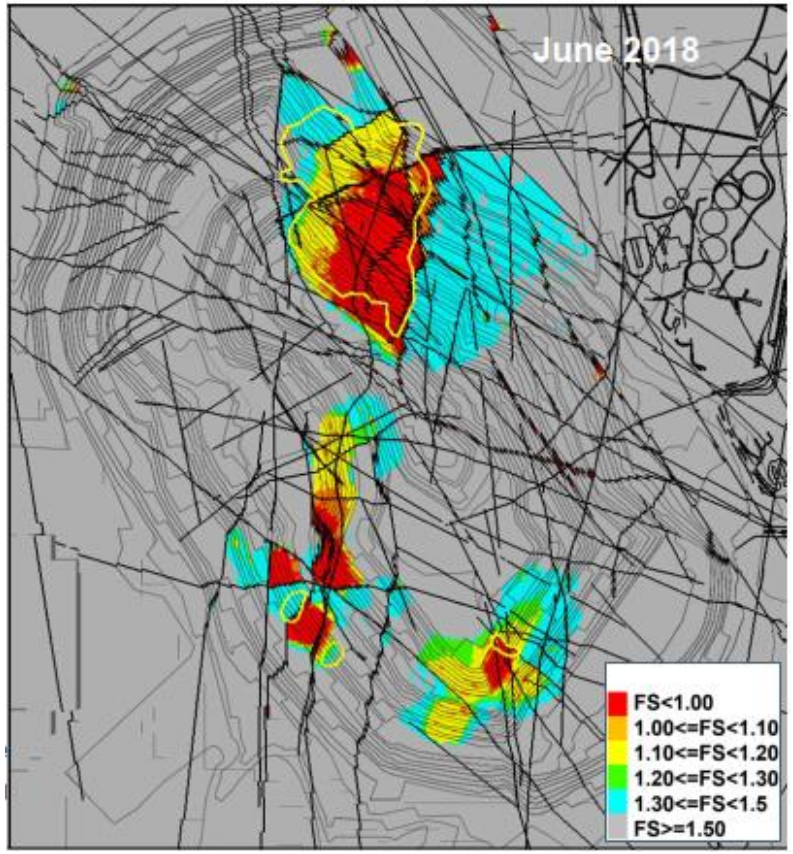
Lower global factor of safety

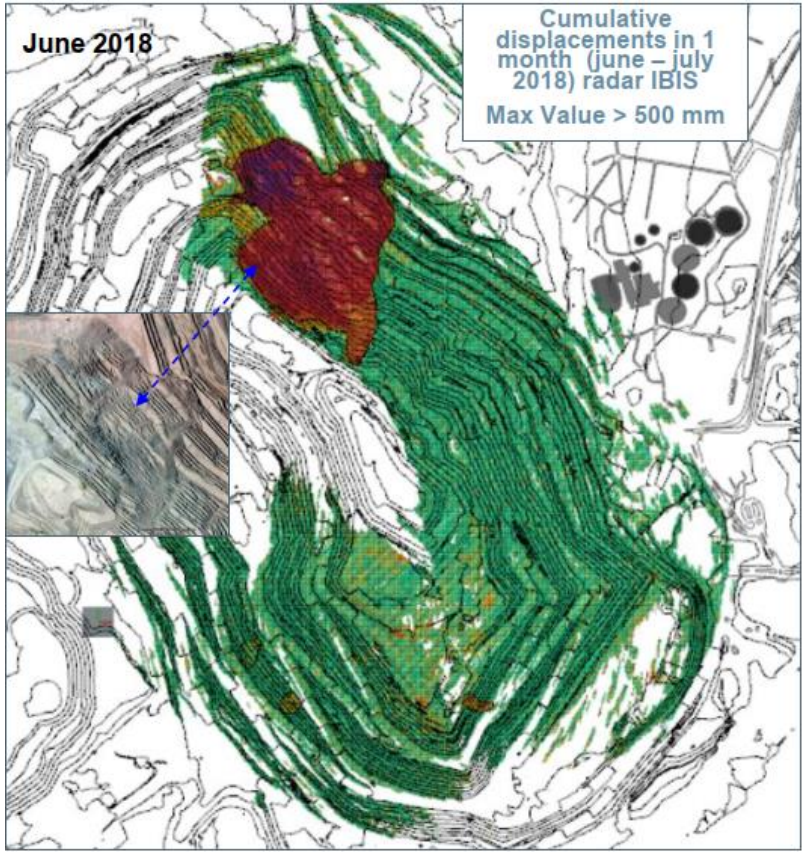
- A lower global factor of safety may require additional design steps.
- If inter ramp walls are found stable, step outs can be allocated to flatter global angle to increase the factor of safety.
- If also inter ramp wall was found unstable, berm width can be increased to flatter inter ramp angle.
- 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

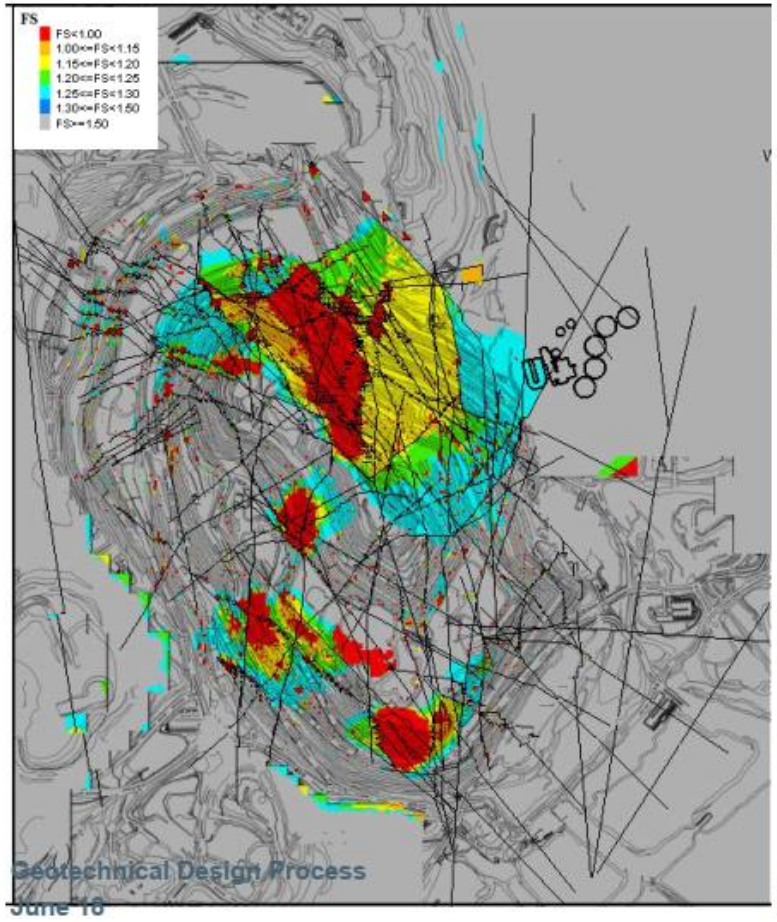
Type of calibration

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

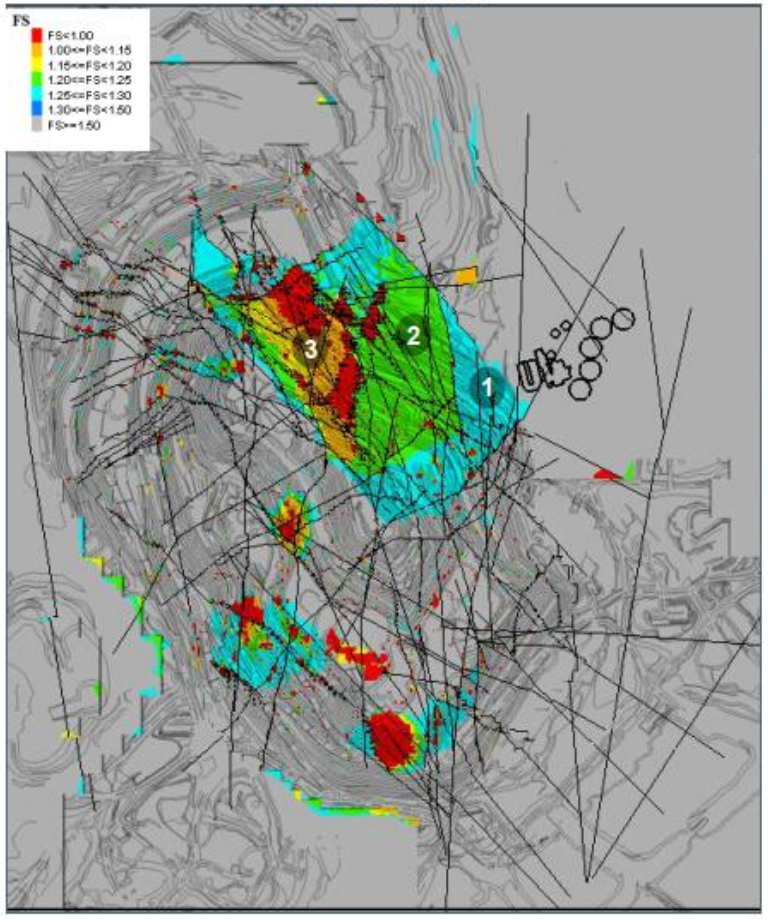
3D Inter ramp and global analysis

Numerical model calibration GSI ± 20%

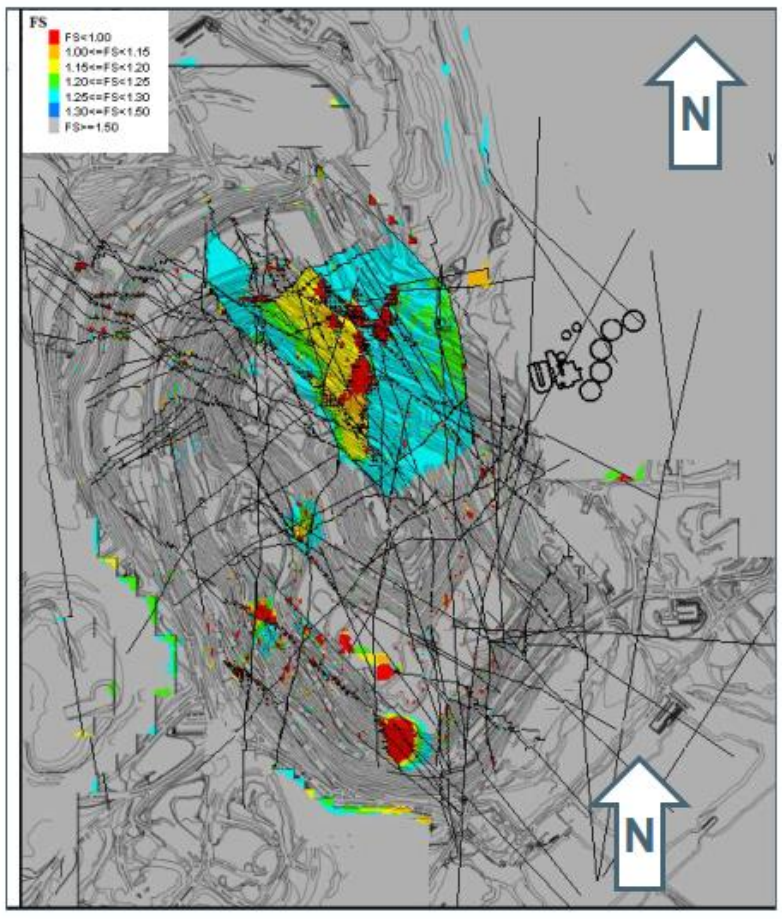
GSI Calibrated -20%



GSI Calibrated



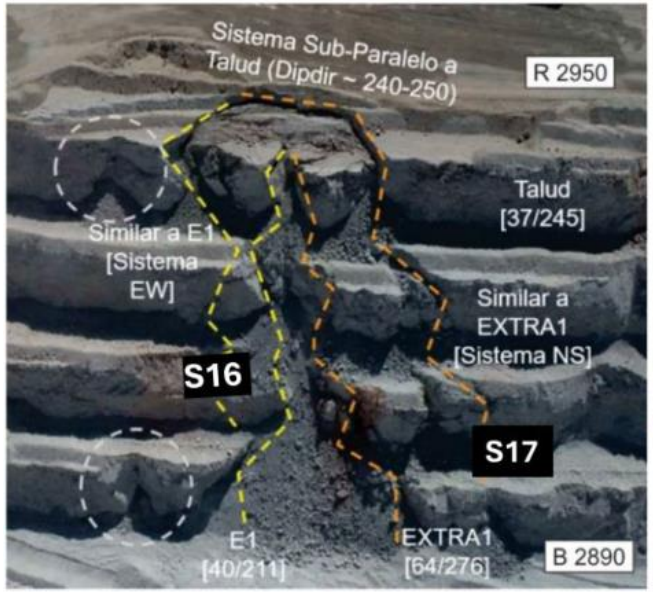
GSI Calibrated +20%

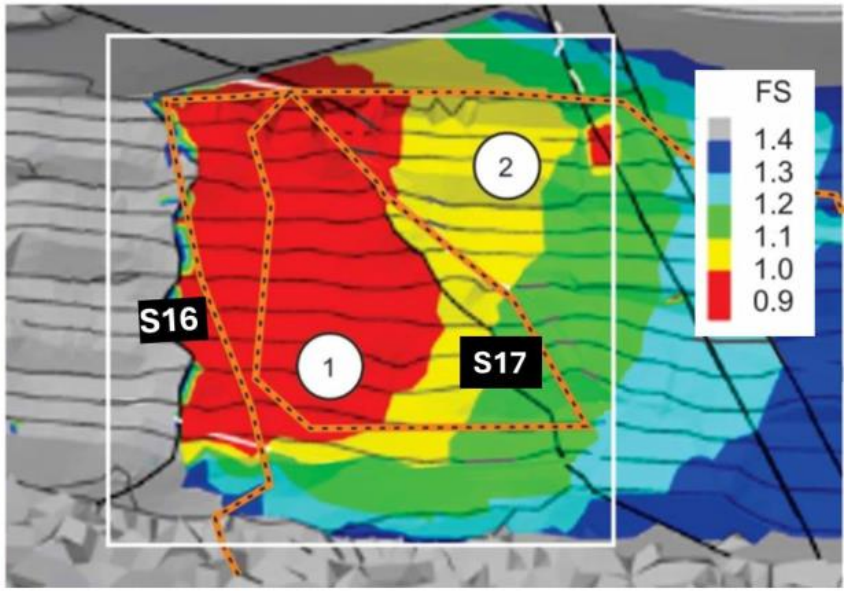


Geotechnical Design Process
June 18

3D Inter ramp and global analysis

Numerical model calibration replicating failure mechanism

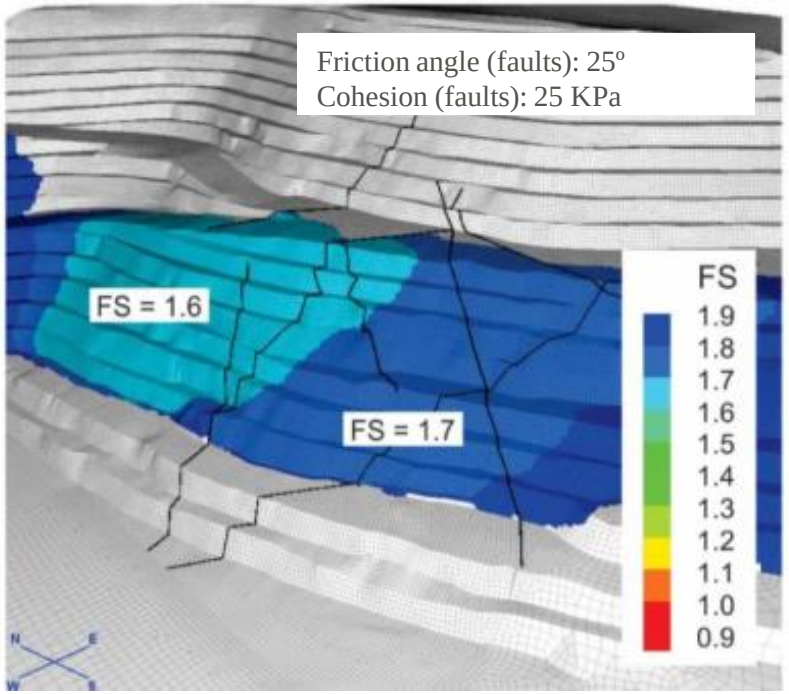


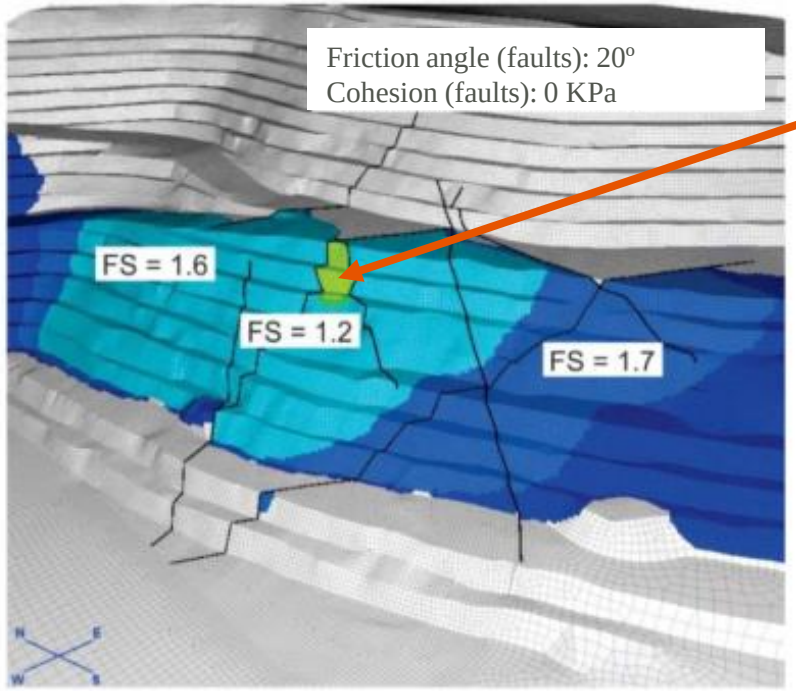


Explicit structures and their properties can be added to the model to better replicate a failure mechanism.

3D Inter ramp and global analysis

Influence of faults in the numerical model

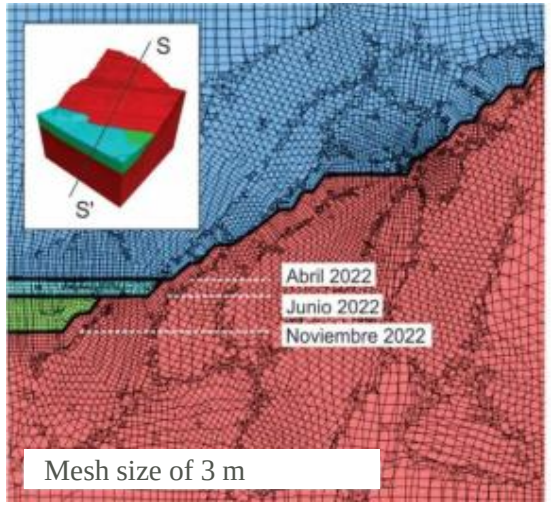


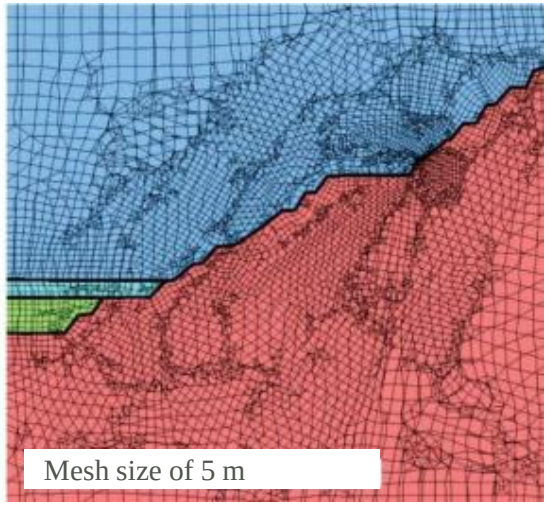


Failure mechanism due to lower properties of fauls

3D Inter ramp and global analysis

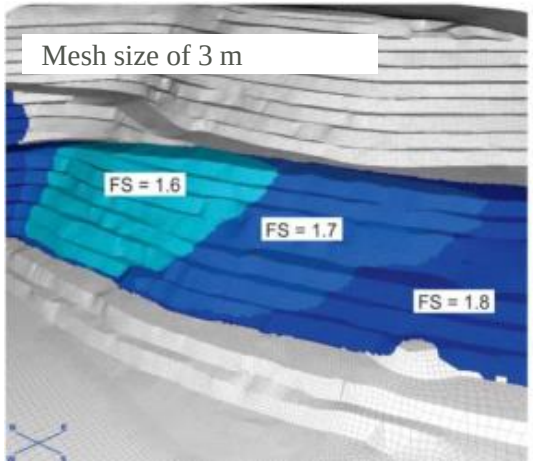
Influence of numerical model setting

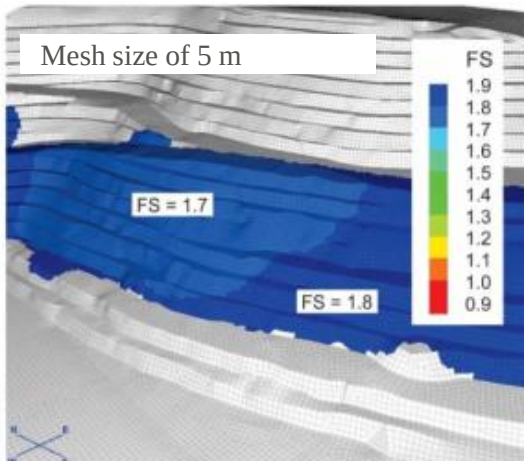




Main aspects:

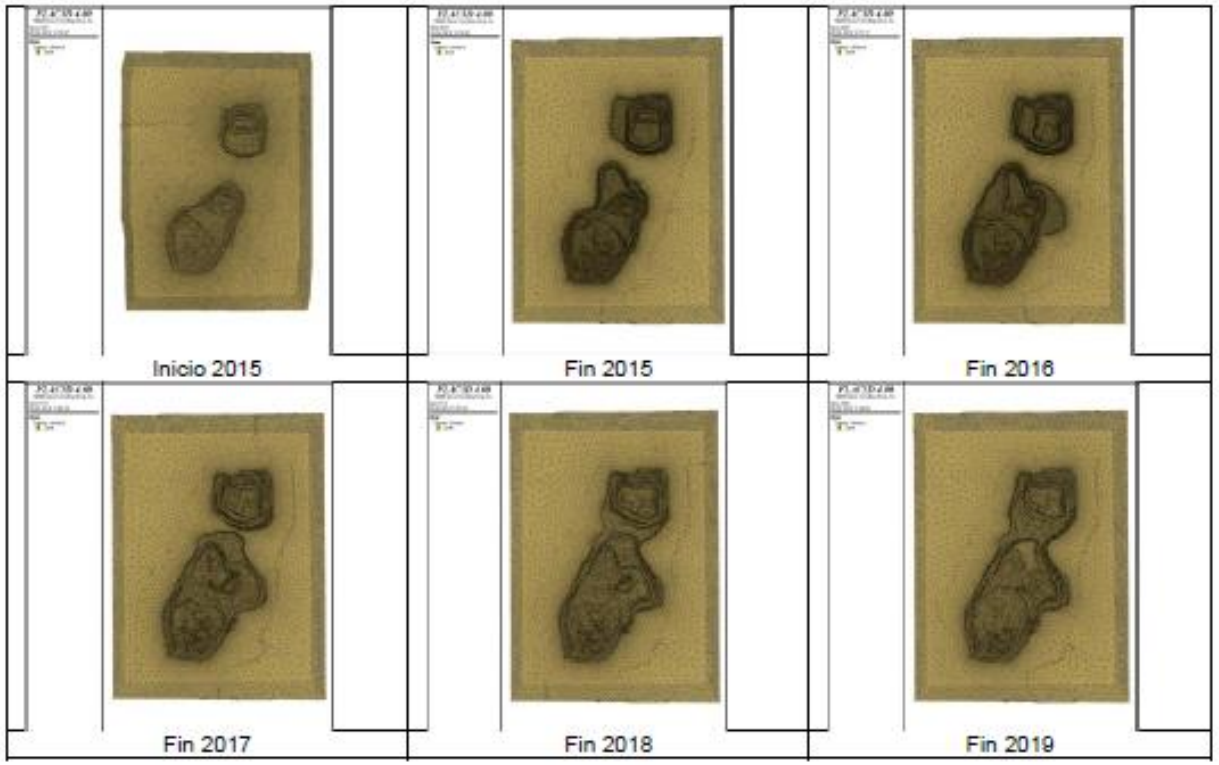
- Mesh size: Coarser mesh may hide potential failures due to 3D geometry aspects, areas of litho contacts, faults.
- Boundary limits: size of the model enough to avoid boundary limit effects introducing artifacts.



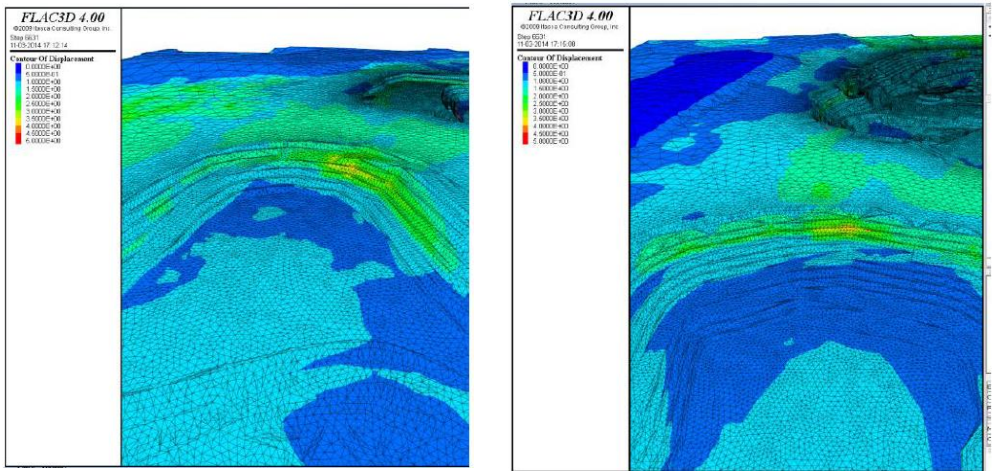


3D Inter ramp and global analysis

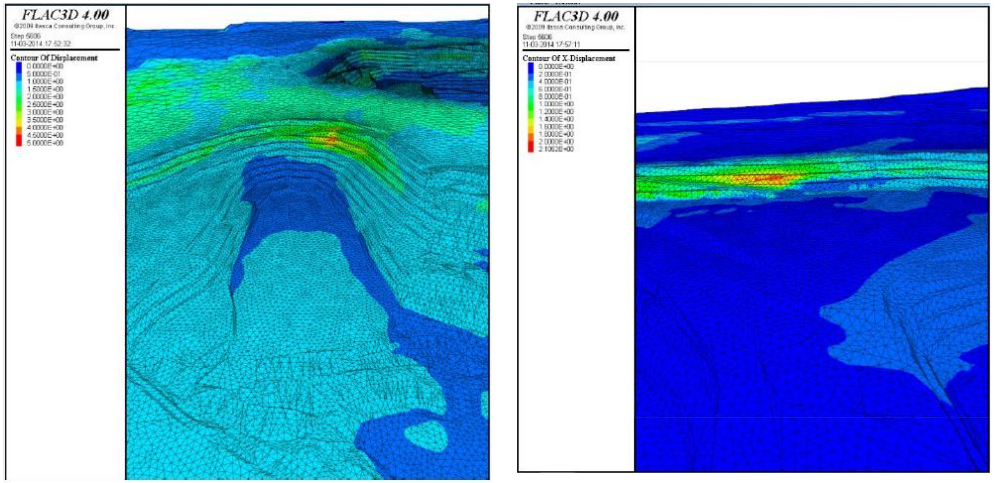
Target to feed monitoring plan



Target areas during FY15

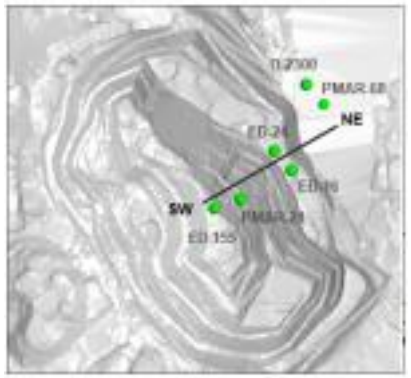


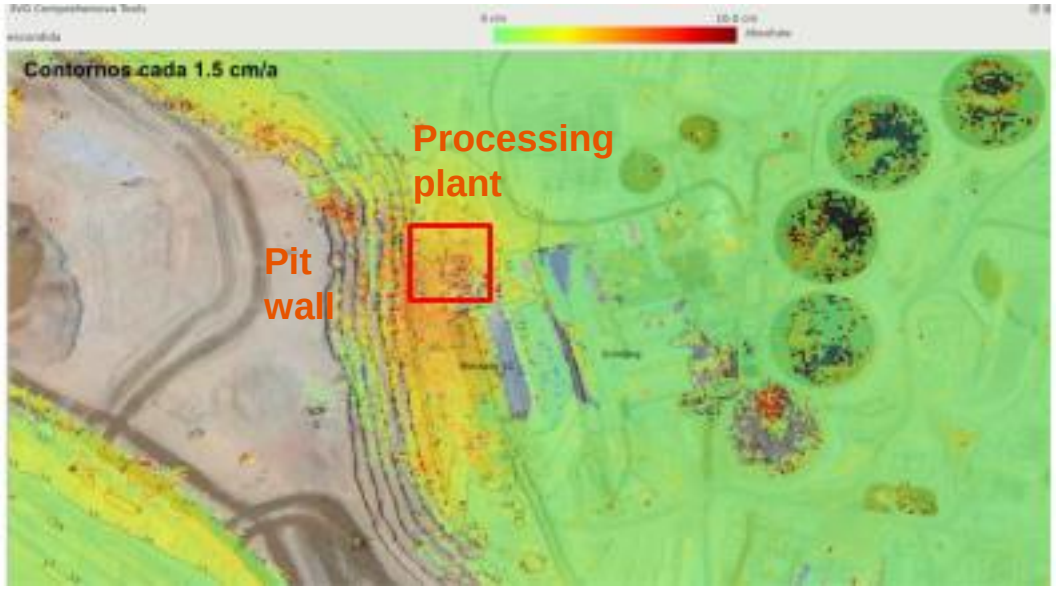
Target areas during FY16



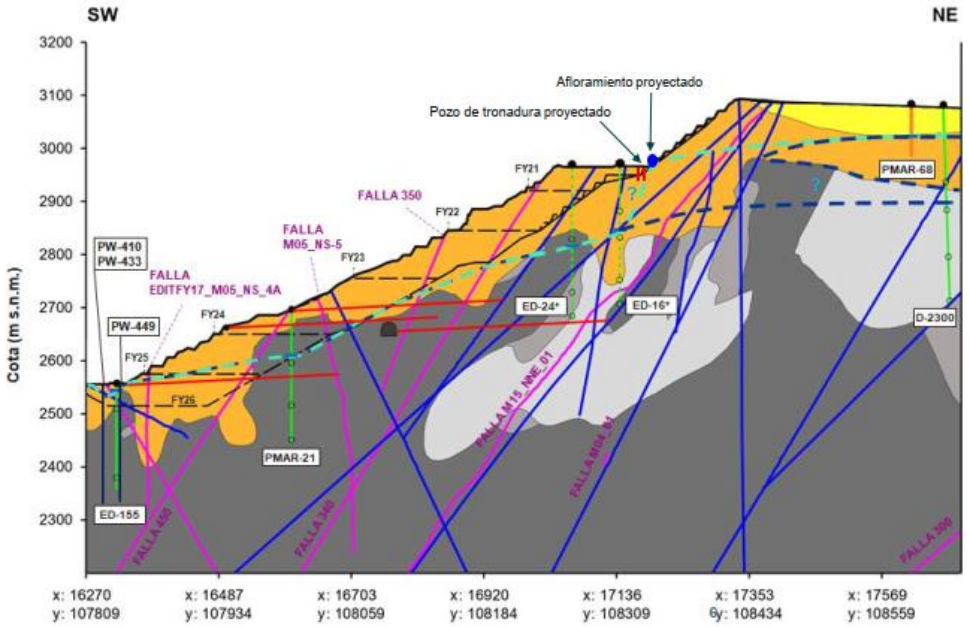
Additional assessments

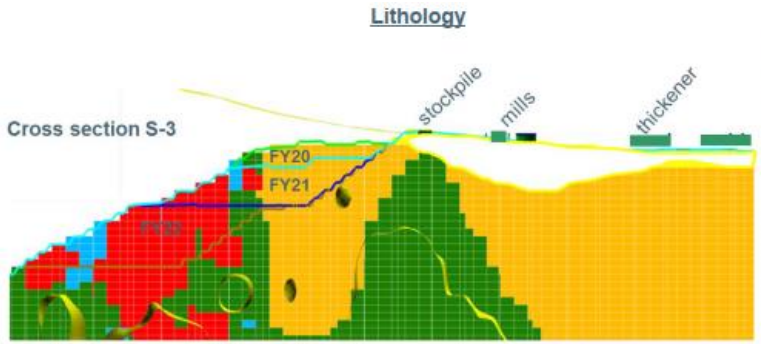
Pit wall interaction with mine infrastructure

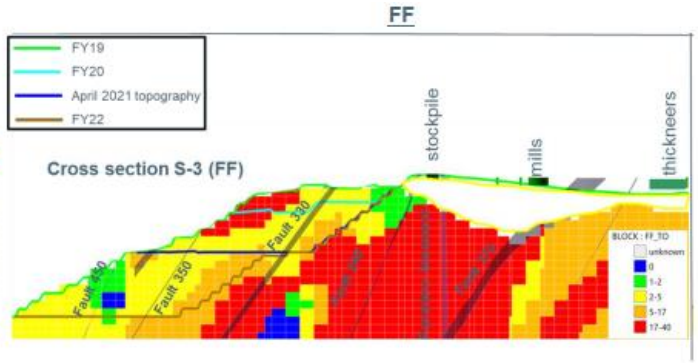




Master section



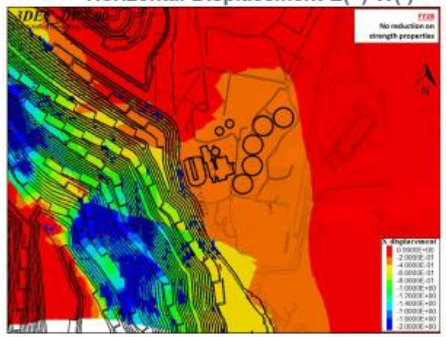




Additional assessments

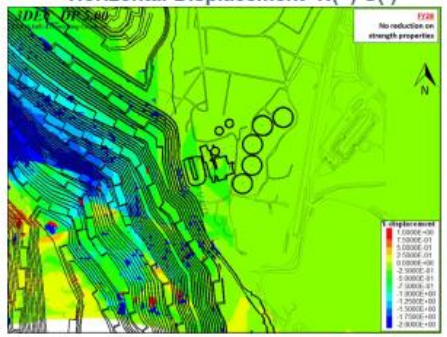
Pit wall interaction with mine infrastructure

Horizontal Displacement E(+)-W(-)



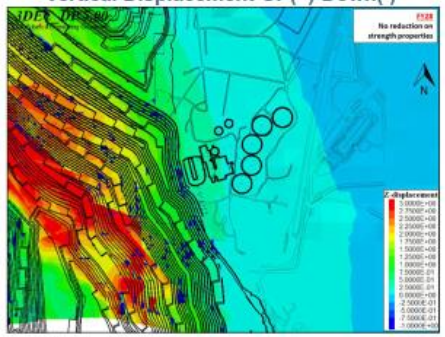
* Displacement up to 20 cm in FY27

Horizontal Displacement N(+)-S(-)

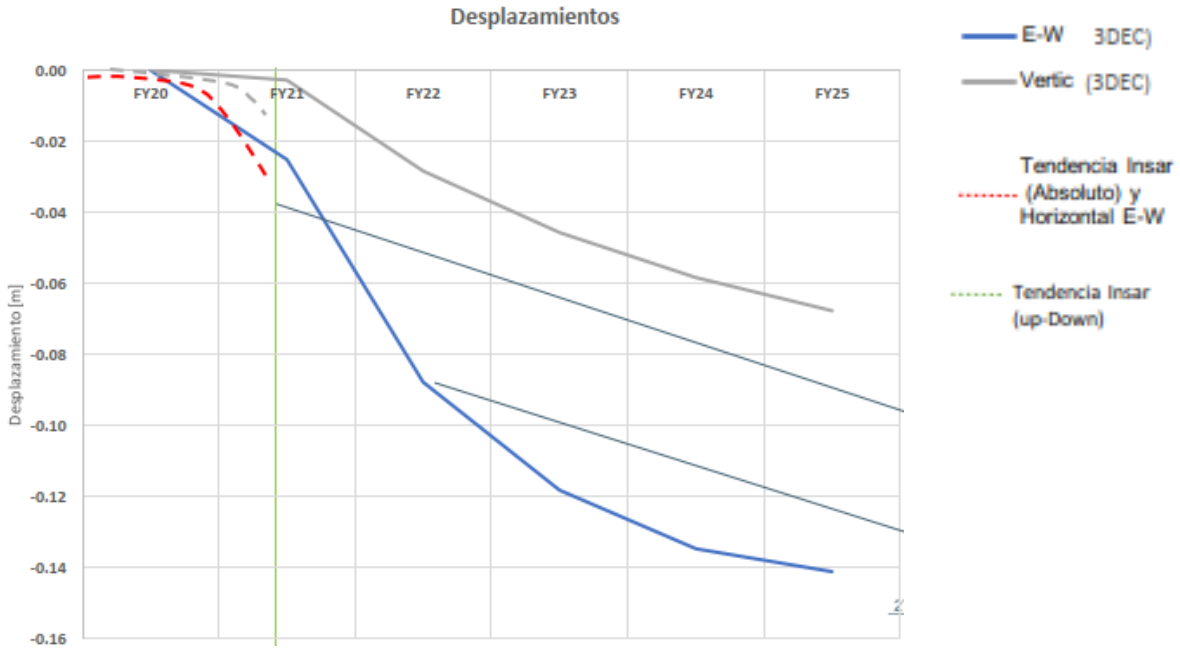


Displacemente up to 25 cm al FY27

Vertical Displacement UP(+)-Down(-)



* Rebound effect issue.



Additional assessments

Ground support


BHP