SASORE

3[er] SIMPOSIO SUDAMERICANO DE EXCAVACIONES EN ROCA

19·20·21 NOVIEMBRE 2018

ISRM

SOCIEDAD CHILENA DE MECÁNICA DE ROCAS

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SOME GEOTECHNICAL CONSIDERATIONS FOR PROBABILISTIC ANALYSIS IN SLOPE DESIGN

ESTEBAN HORMAZABAL

Managing Director

SRK Consulting Chile

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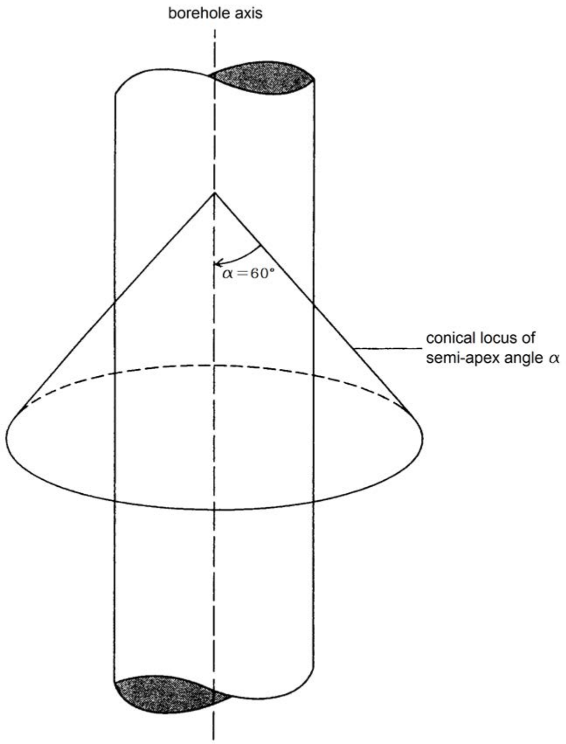
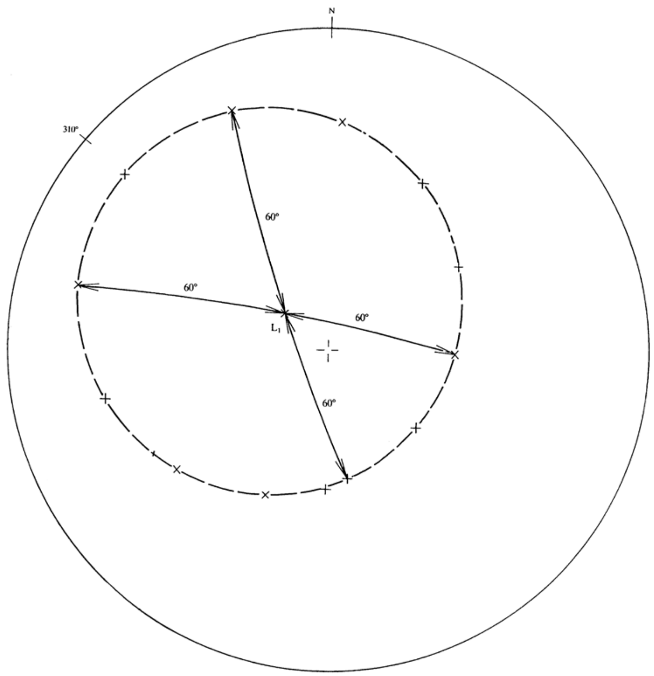
Some geotechnical considerations for probabilistic analysis in slope design

INTRODUCTION

1) GEOTECHNICAL CHARACTERIZATION.
2) BENCH BERM DESIGN.
3) INTERRAMP AND OVERALL SLOPE STABILITY.
4) GEOTECHNICAL RISK MAP.

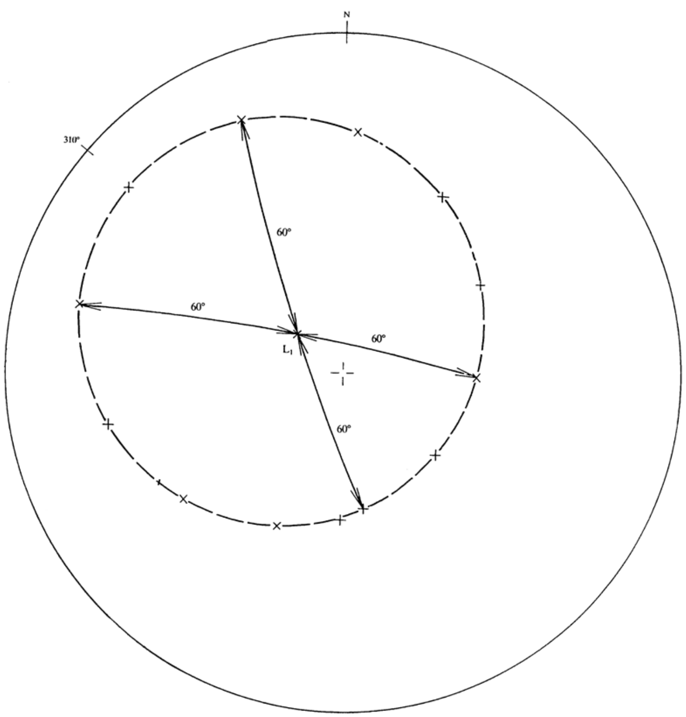
Camera rotation ⟹ geometrical cone in the stereographic projection.

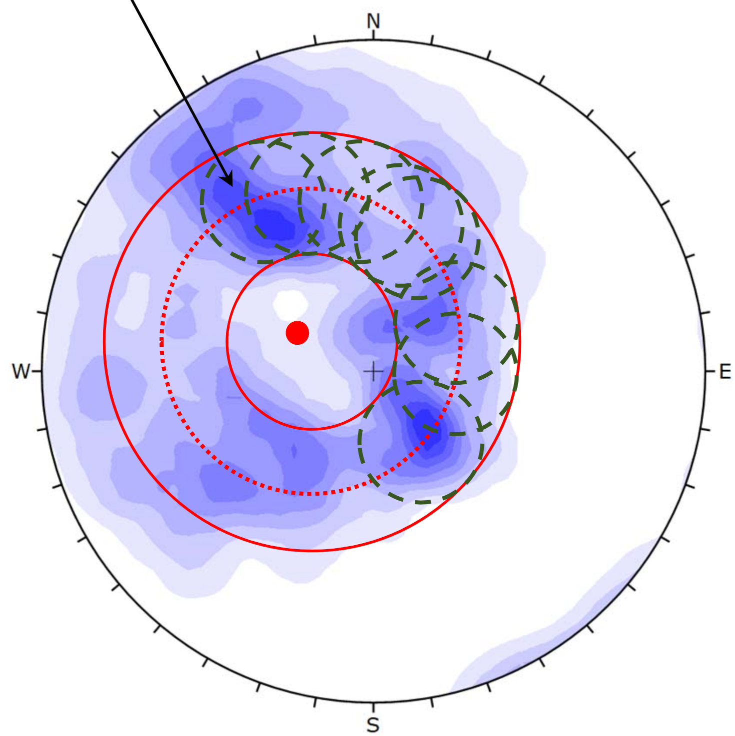




Priest, S. D. (1985): *Hemispherical Projection Methods in Rock Mechanics*, George Allen and Unwin, London.

Principal structural set mapped on surface with randomly rotation.





Stereographic projection from ATV survey in a geotechnical borehole.

Examples of natural joints/minor faults classified as mechanical.






Examples of wrong calculation of RQD.

From_Depth	To_Depth	Interval	RQD_m	RQD_Pct
30	33	3	3	100

Geotechnical Characterization

Overestimation of FF/m and sub estimation on the classification systems indexes.

Desde (m)	Hasta (m)	Tramo Molido (m)	FF_FINAL (f/m)	GSI_R1	GSI_R2	RMR_B89	RMR1_L90	RMR2_L90	Q'
291	294	0.55	10.67	20	25	48	26	35	3.36

Crushed material of 0,55m that can not be observed.

Desde (m)	Hasta (m)	Tramo Molido (m)	FF_FINAL (f/m)	GSI_R1	GSI_R2	RMR_B89	RMR1_L90	RMR2_L90	Q'
309	312	1.5	22.67	15	20	39	22	29	0.42

Crushed material of 1,5m that can not be observed.

FF/m calculation

In many database, FF/m is determined as joint total count of borehole length divided for the recovery length. No correction are applied based on dip angle different regarding with the borehole orientation:

$$FF = \sum_{i=1}^{N} FF_i \cos\theta_i$$

There is also corrections if Laubscher (1990) classification system need to be applied.

TABLE II
FACTORS TO GIVE AVERAGE FRACTURE FREQUENCY

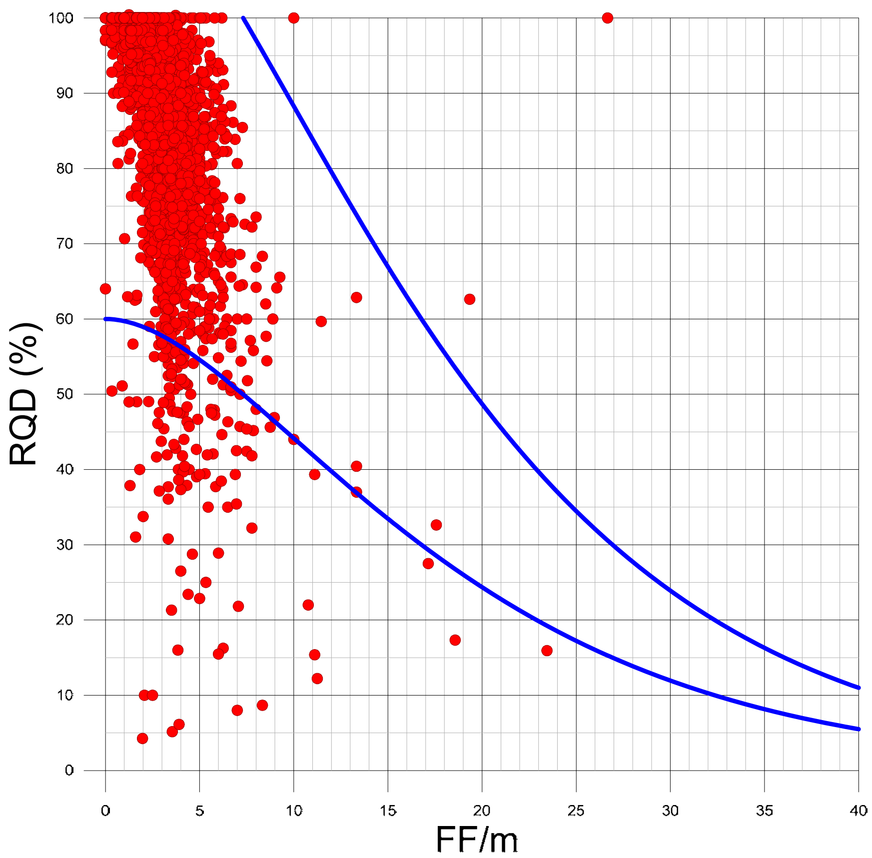
Sampling procedure	Factor
a. One set of three sets on a line, or one set only	1,0
b. Two sets of three sets on a line or two sets only	1,5
c. All of the sets on a line or borehole core	2,0
d. Two sets on one line and one on another	2,4
e. Three sets on three lines at right-angles	3,0

$$\text{Average frequency} = \frac{\text{Sum of individual FF/m (inverse of spacing)}}{2}$$

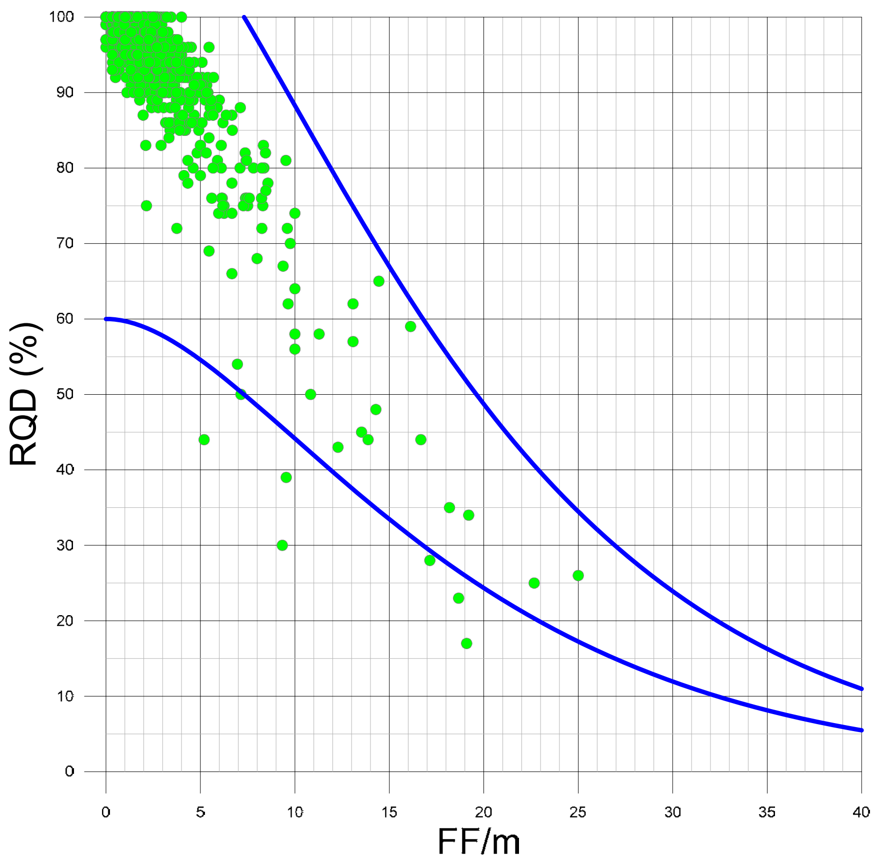
Desde (m)	Hasta (m)	RECUPERACIÓN (m)	J_30 (f/3m)	J_60 (f/3m)	J_90 (f/3m)	FF (f/m)
411	414	3	4	2	0	2

FF/m
3.03

Geotechnical Characterization

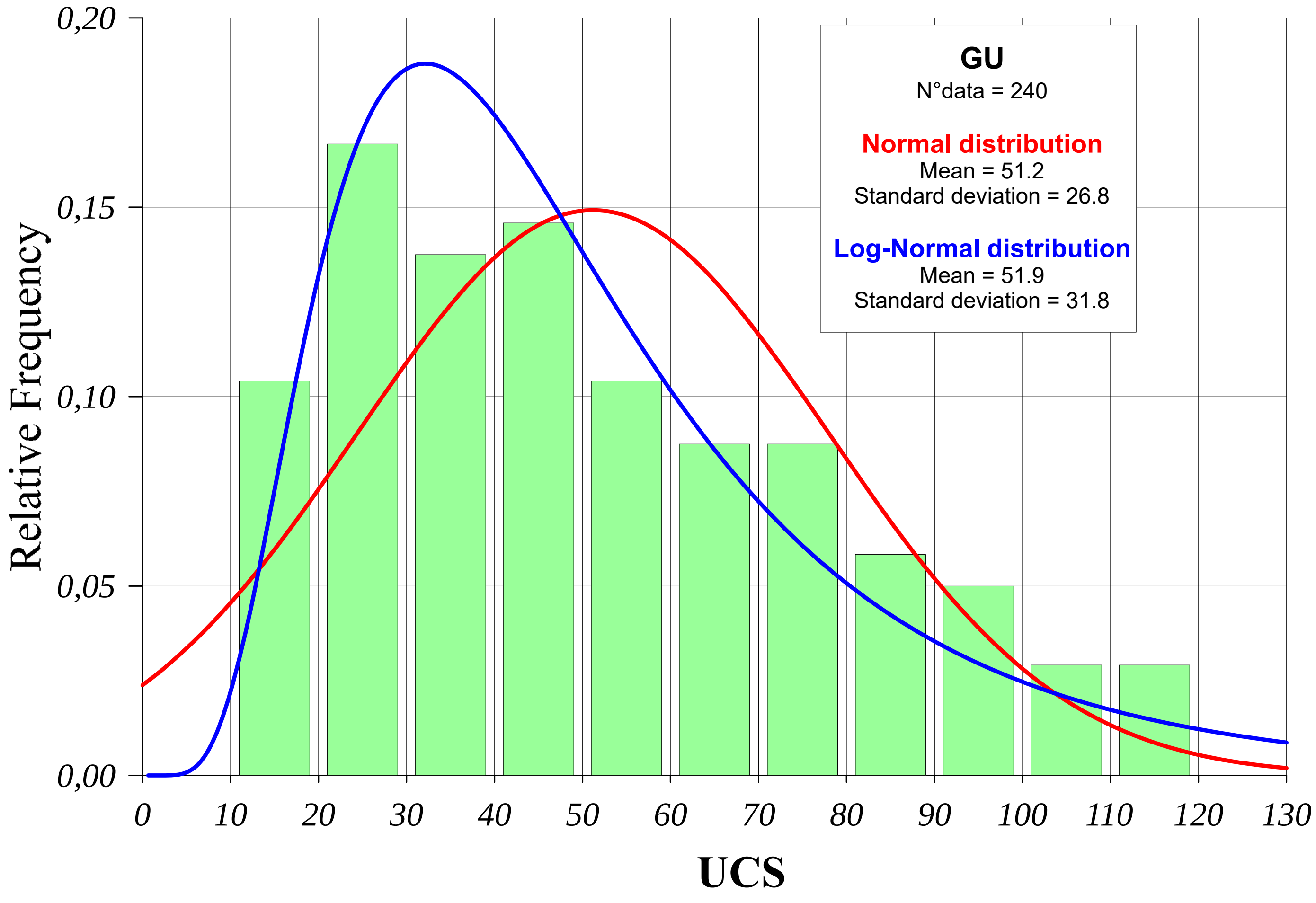


ORIGINAL DATABASE

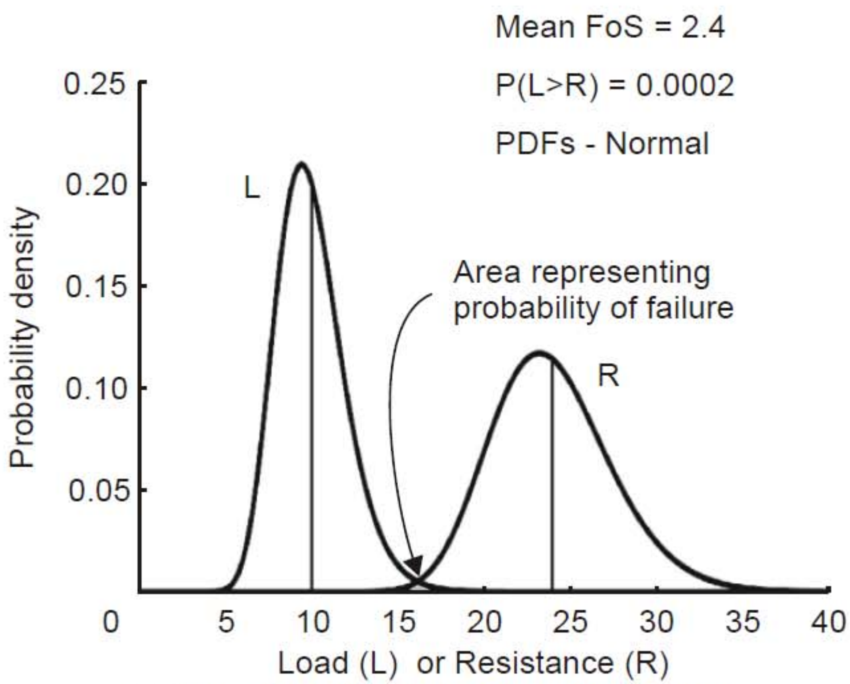


CORRECTED DATABASE

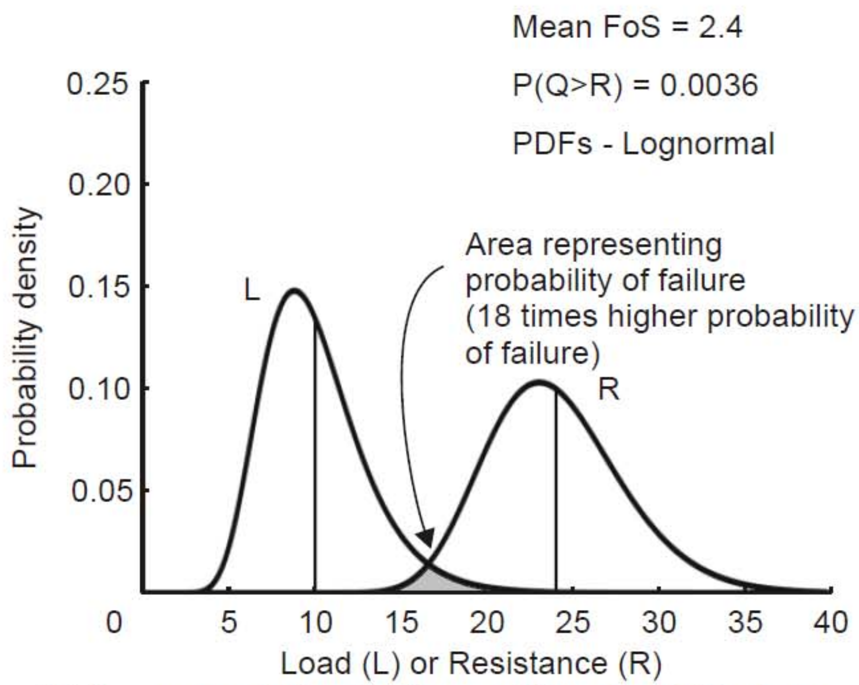
UCS tests results



PDFs Distribution



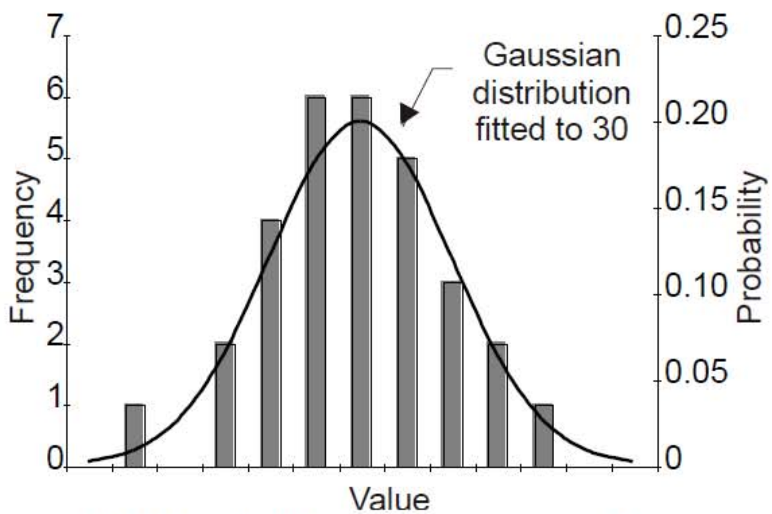
a) Normal PDFs of Load and Resistance



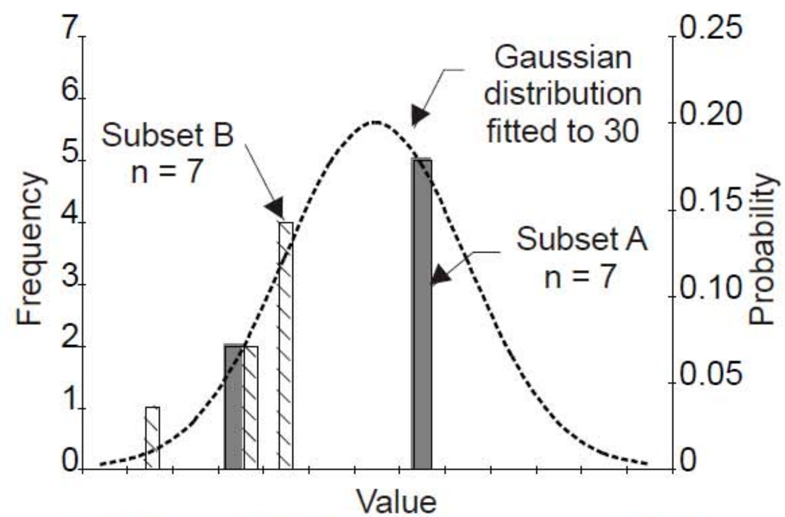
b) Lognormal distributions of Load and Resistance

Naghibi, 2010

Database Uncertainty



a) Data exhibiting aleatory uncertainty



b) Data exhibiting epistemic uncertainty

Bedi & Harrison (2012)

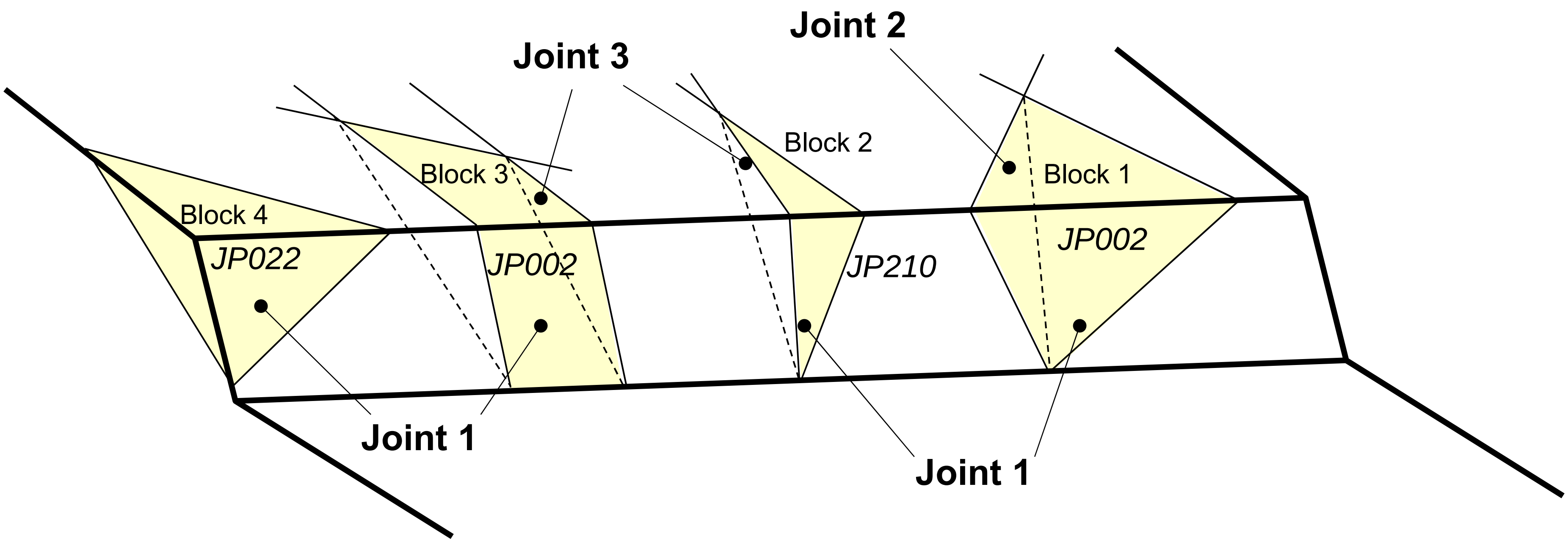
Bench Berm Design

Owing to the large number of discontinuities exposed daily in producing open pit mines, a probabilistic approach to evaluating the potential for blocks/wedges to fail is required.

A computer program which uses joints orientation, persistence and spacing statistics must be implemented to develop a probabilistic approach which allows rapid determination of the probability of failure of blocks/wedges for different benches geometries.

Bench Berm Design

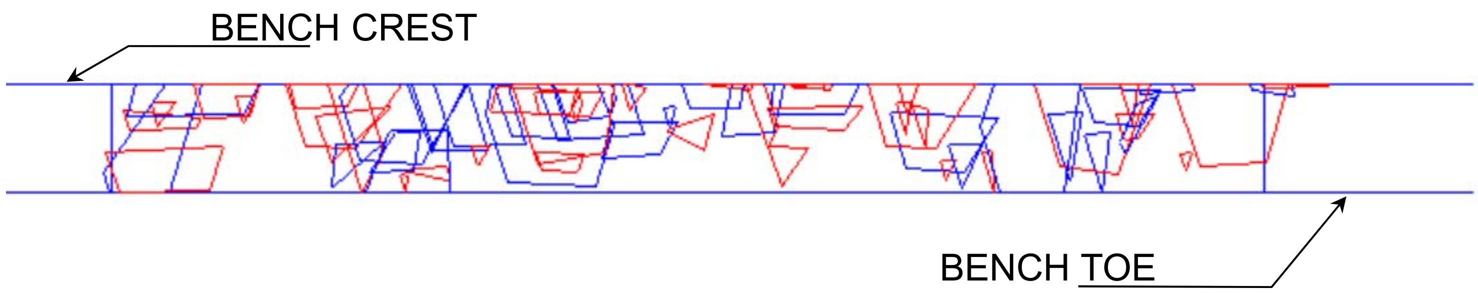
By applying the keyblock analysis method of Goodman & Shi (1985) each simulated block can be evaluated to determine whether it is removable from the surrounding rock mass.



Removable blocks in a rock slope

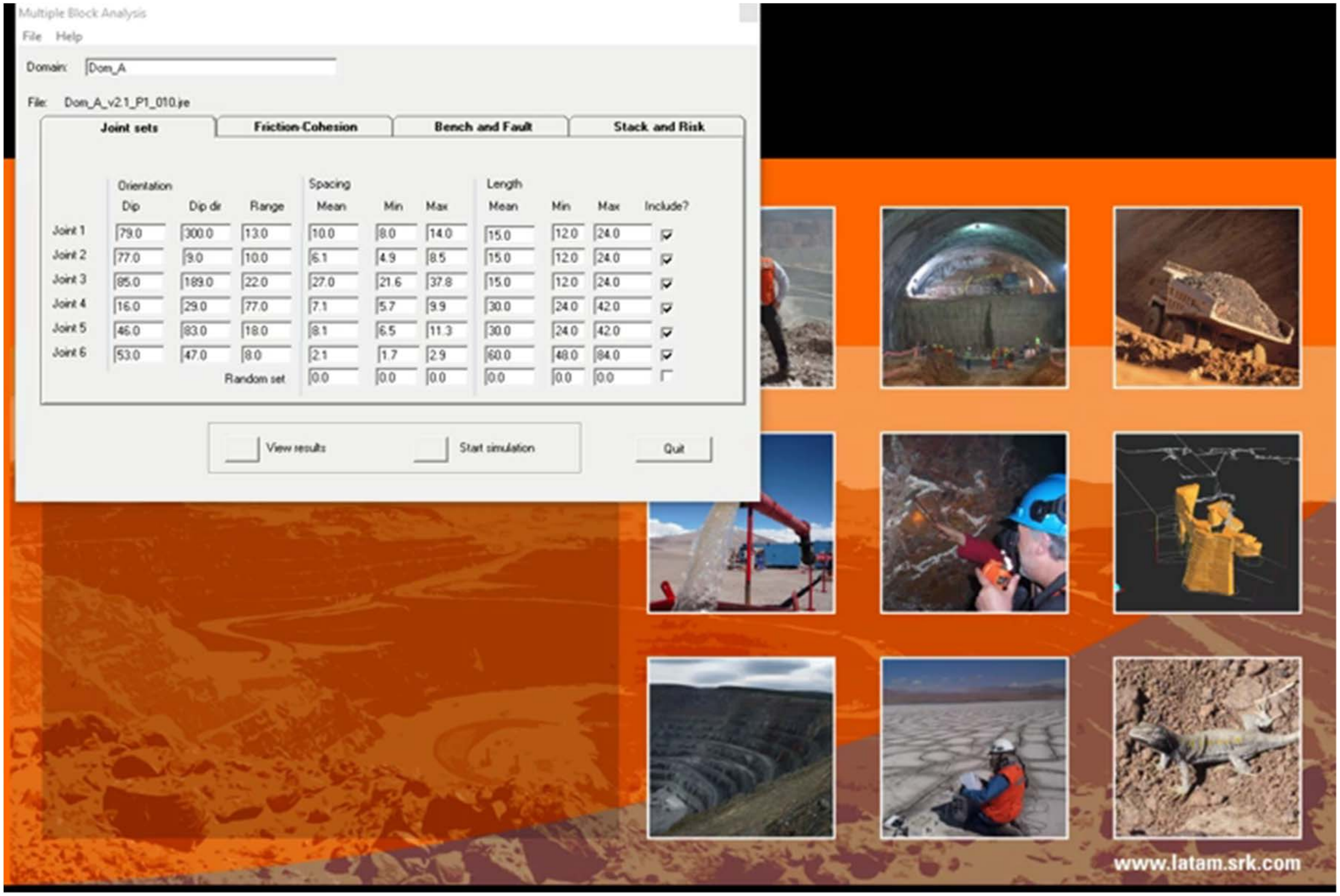
Bench Berm Design

Once a keyblock has been identified, its removability and sliding stability is assessed and accumulated so that the stability of a pit bench can be evaluated.



Random locations of blocks along a bench. Red blocks are unstable (SBlock output)

Bench Berm Design


Multiple Block Analysis
File Help
Domain: Dom_A
File: Dom_A_v2.1_P1_010.jre
Joint sets | Friction-Cohesion | Bench and Fault | Stack and Risk

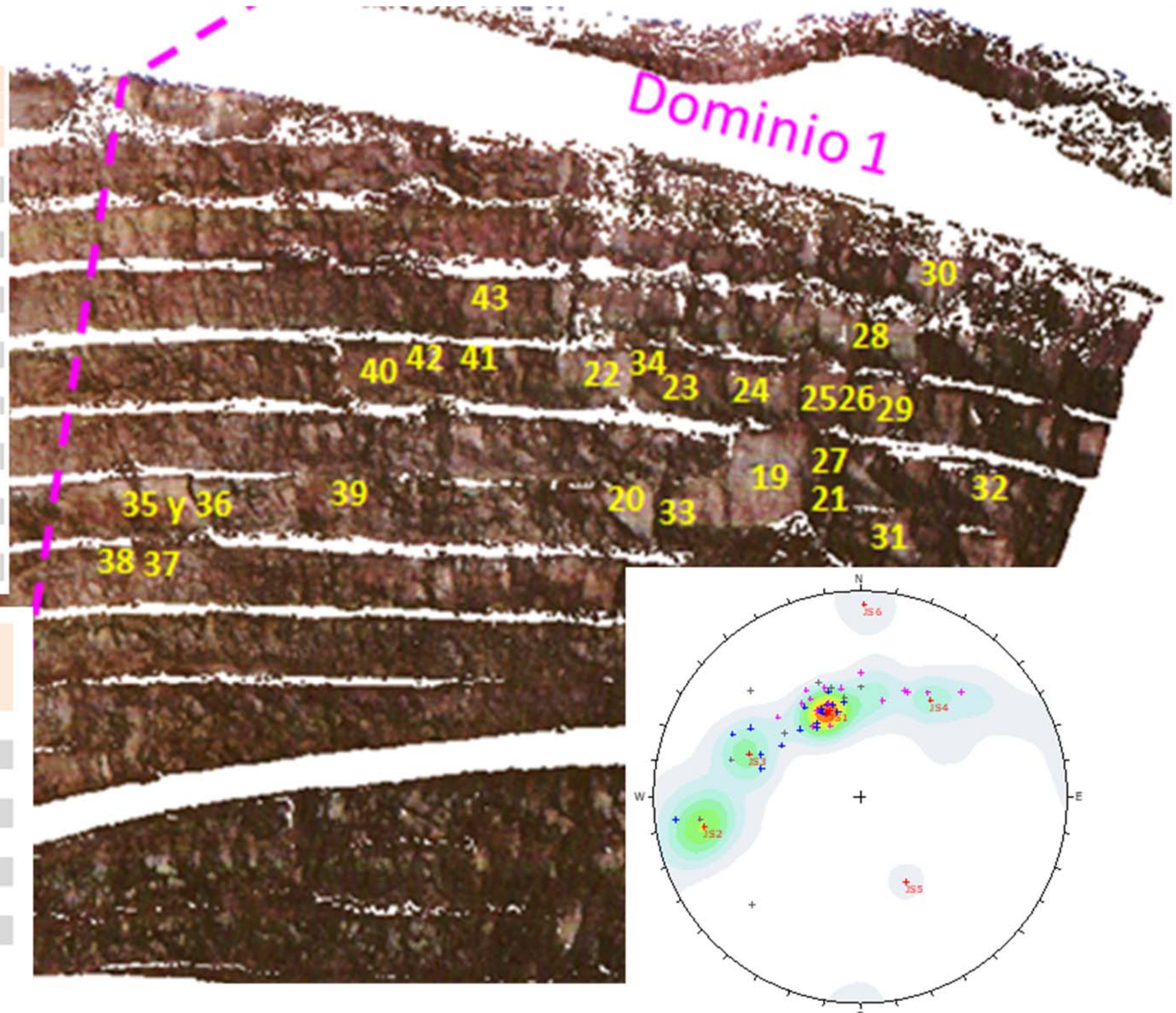
	Orientation Dip	Dip dir	Range	Spacing Mean	Min	Max	Length Mean	Min	Max	Include?
Joint 1	79.0	300.0	13.0	10.0	8.0	14.0	15.0	12.0	24.0	☑
Joint 2	77.0	9.0	10.0	6.1	4.9	8.5	15.0	12.0	24.0	☑
Joint 3	85.0	189.0	22.0	27.0	21.6	37.8	15.0	12.0	24.0	☑
Joint 4	16.0	29.0	77.0	7.1	5.7	9.9	30.0	24.0	42.0	☑
Joint 5	46.0	83.0	18.0	8.1	6.5	11.3	30.0	24.0	42.0	☑
Joint 6	53.0	47.0	8.0	2.1	1.7	2.9	60.0	48.0	84.0	☑
Random set				0.0	0.0	0.0	0.0	0.0	0.0	☐

View results Start simulation Quit

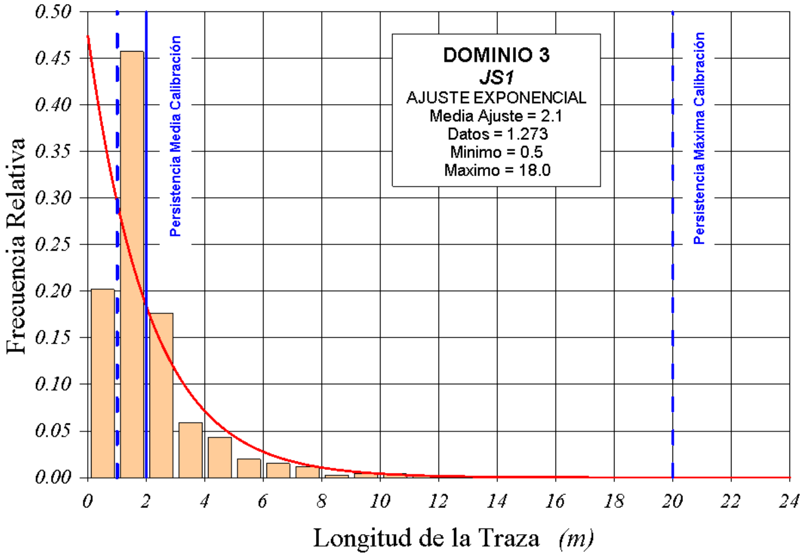
I-Site Calibration

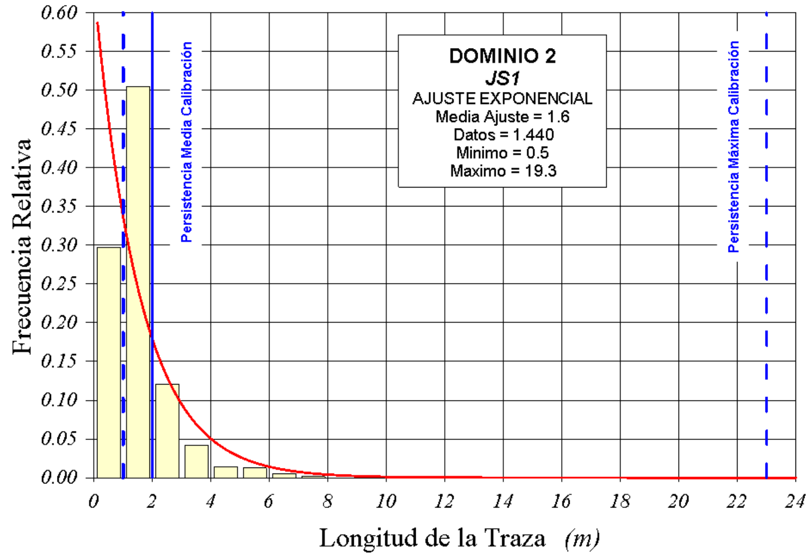
Dominio 1		
DipDir 170°		
ID	Dip	DipDir
19	50	153
20	45	146
21	58	204
22	58	134
23	56	170
24	56	153
25	56	148
26	70	224
27	58	203
28	62	213
29	60	153
30	58	162
31	41	157
32	51	161
33	51	193
34	62	180

Dominio 1		
DipDir 150°		
ID	Dip	DipDir
35	51	130
36	73	45
37	57	165
38	76	82
39	52	171
40	61	160
41	56	180
42	66	106
43	73	134

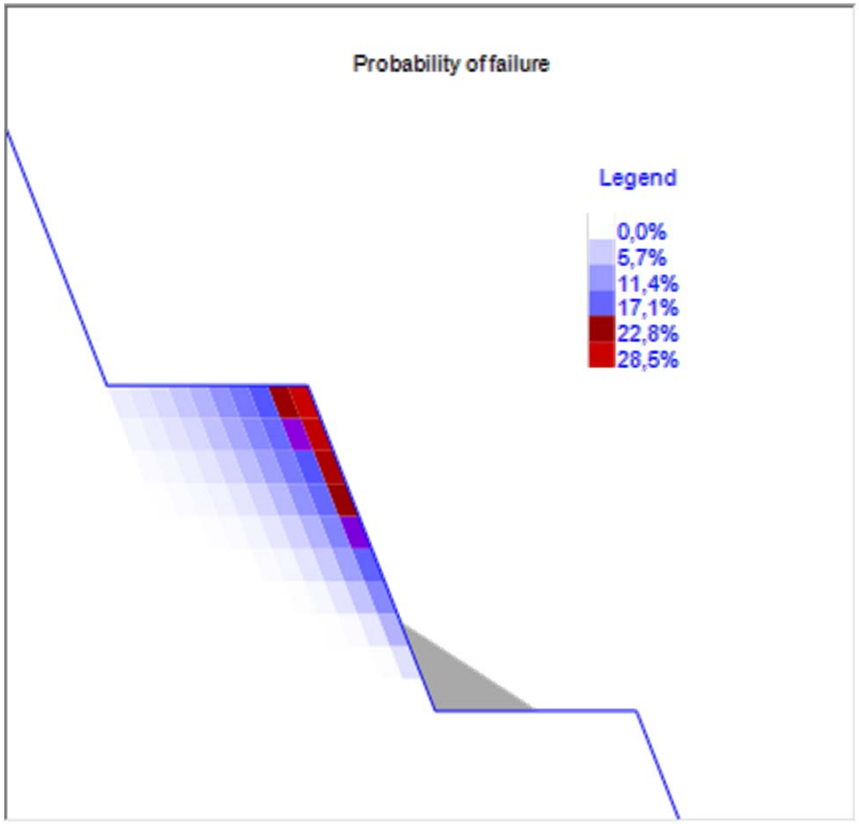


I-Site Calibration (Persistence)



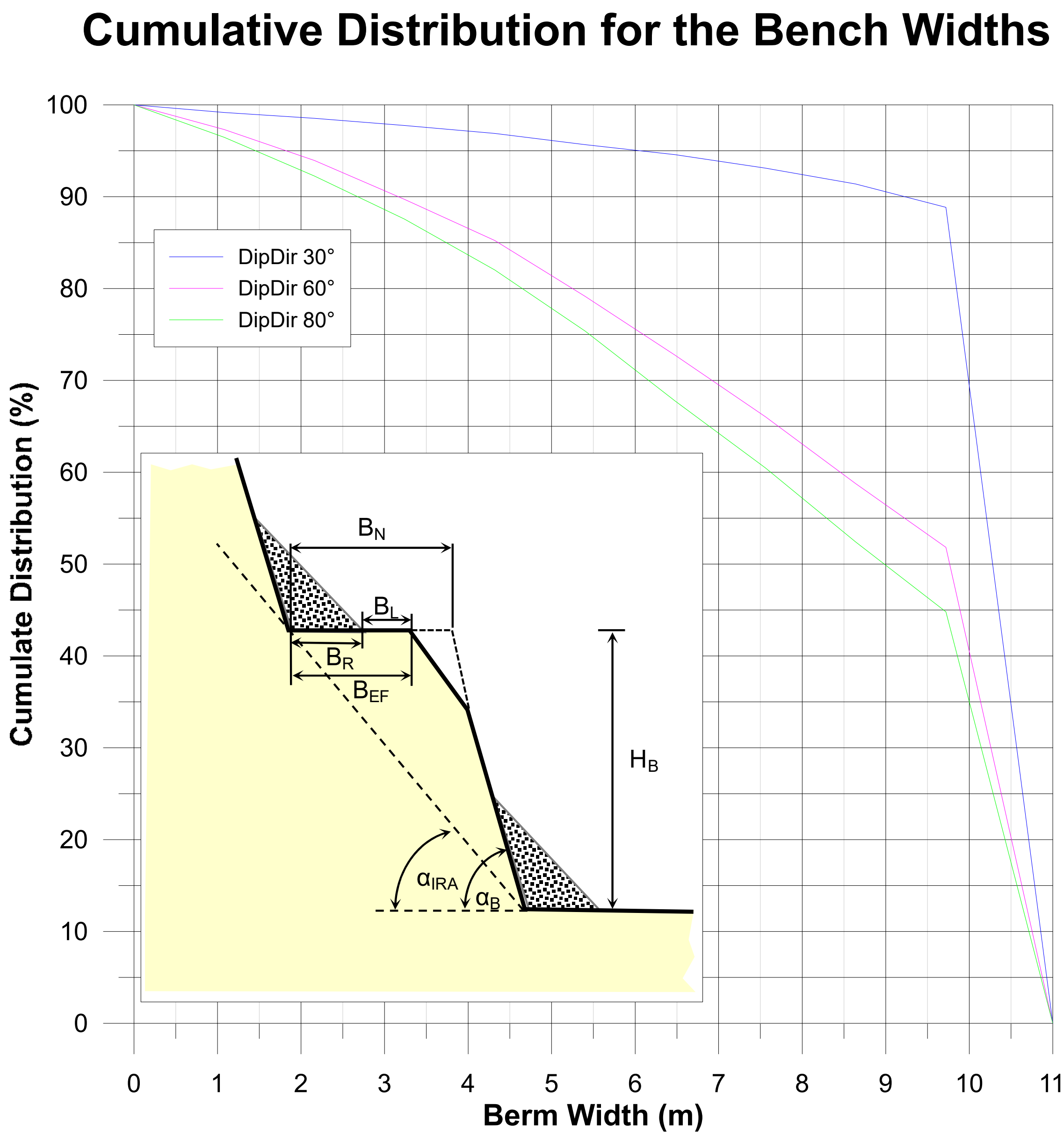


Back-Break calculation



This screen shows the probability of failure expressed as a depth of failure of a bench (SBlock output)

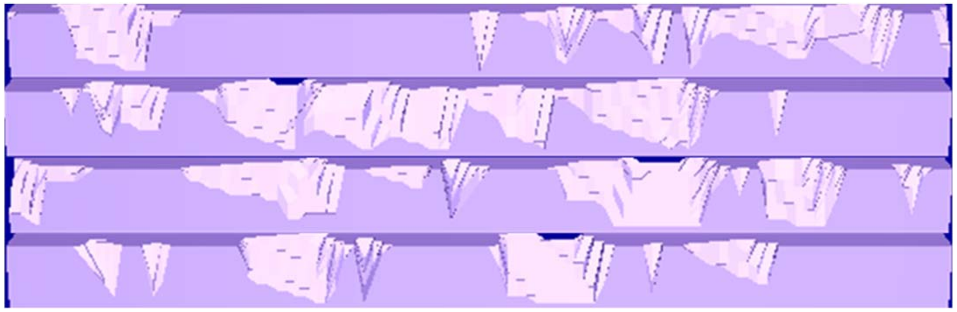
Back-break and spill material or pile of rubble (SBlock output)



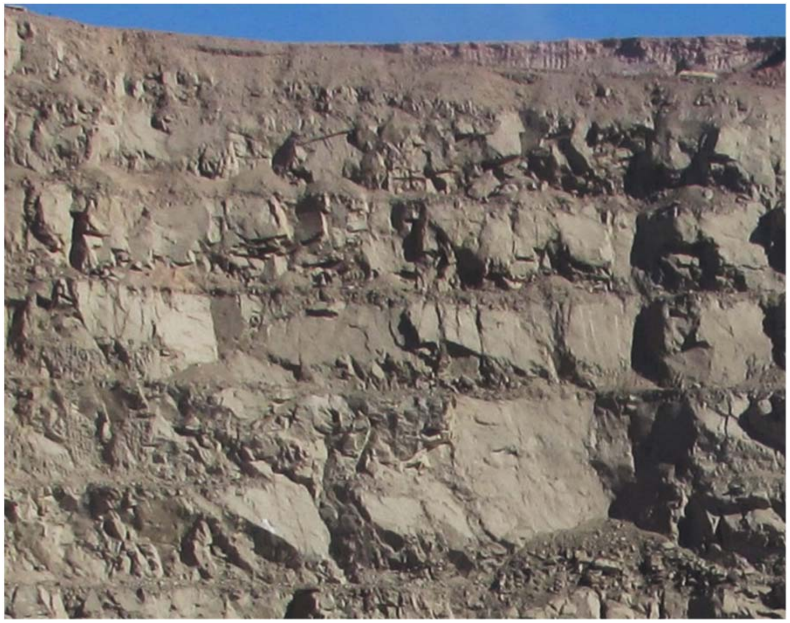
90% of the benches will be greater than 9,5 m (SBlock output)

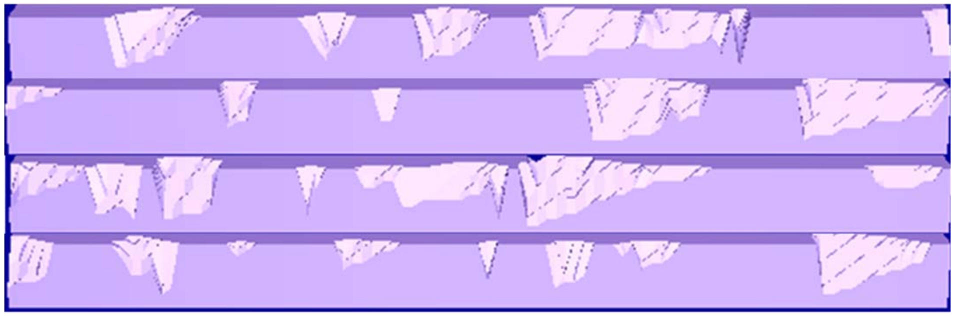
Bench Berm Design

Calibration



PoF > 30 %

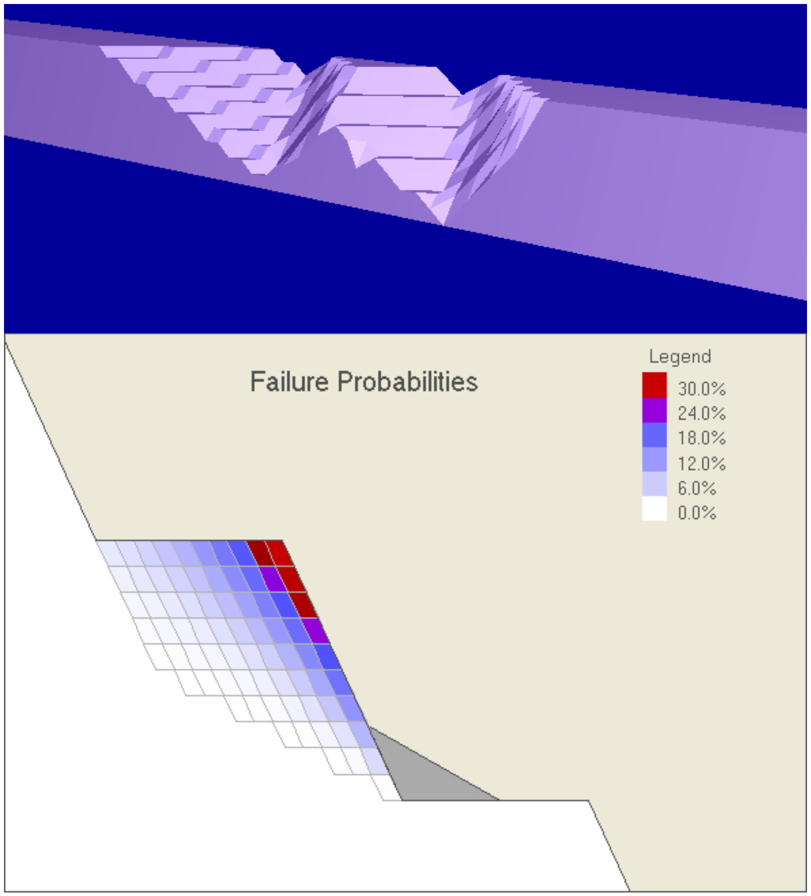




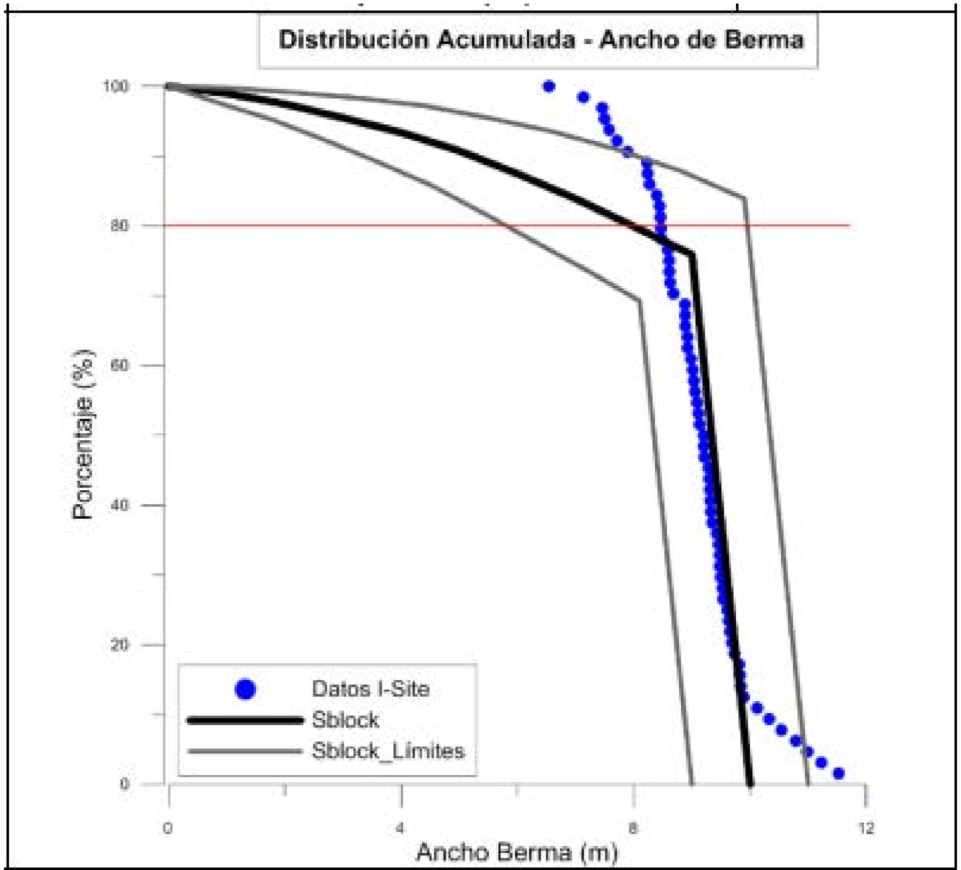
20 % < PoF < 30 %

Bench Berm Design

Calibration

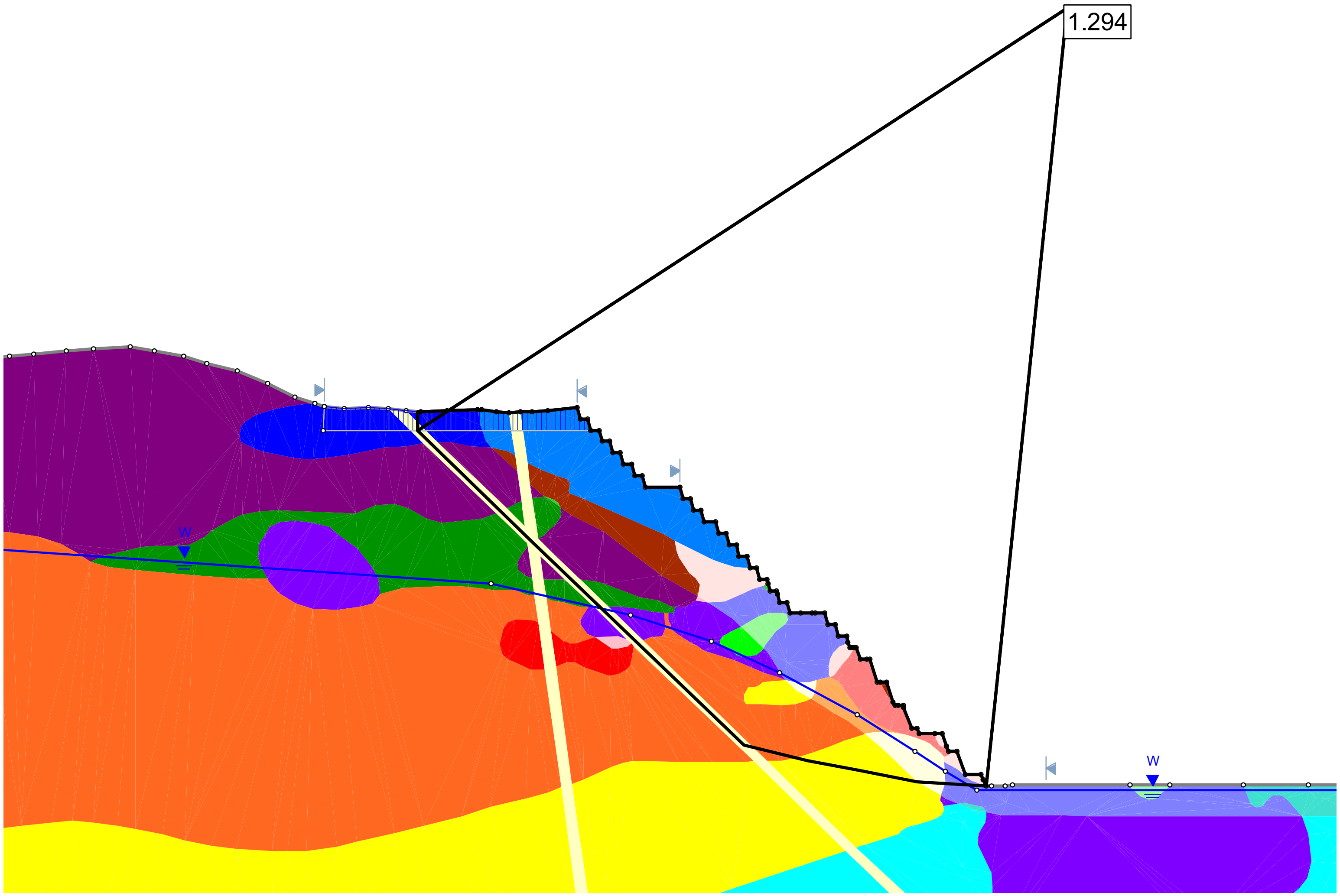


Calibration



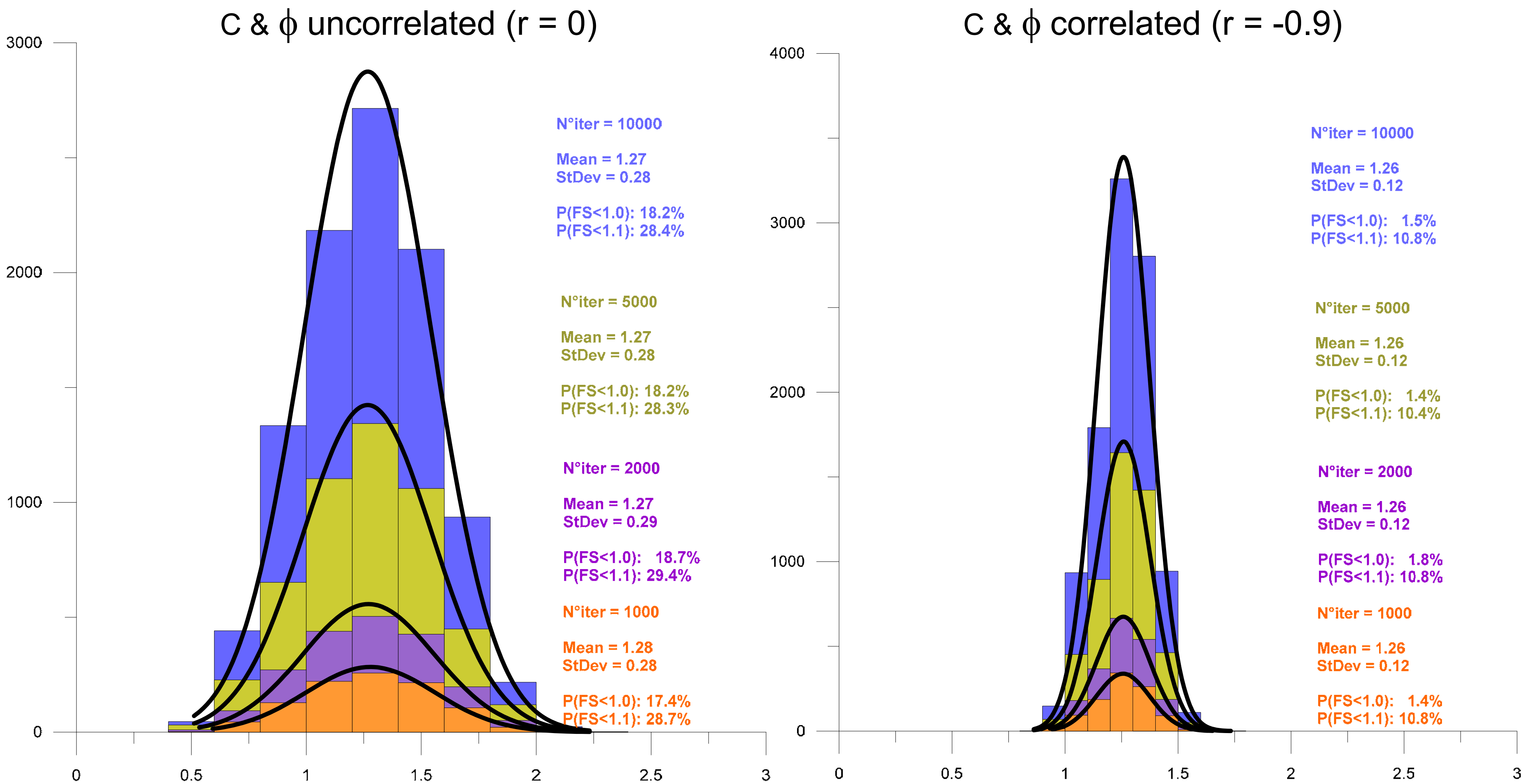
Límite inferior estimado	5.9 m
Estimación con Teoría de Bloques / SBlock	8.0 m
Escaneo ancho de bermas I-Site	8.4 m
Límite superior estimado	10 m

Interramp and Overall Stability Analysis



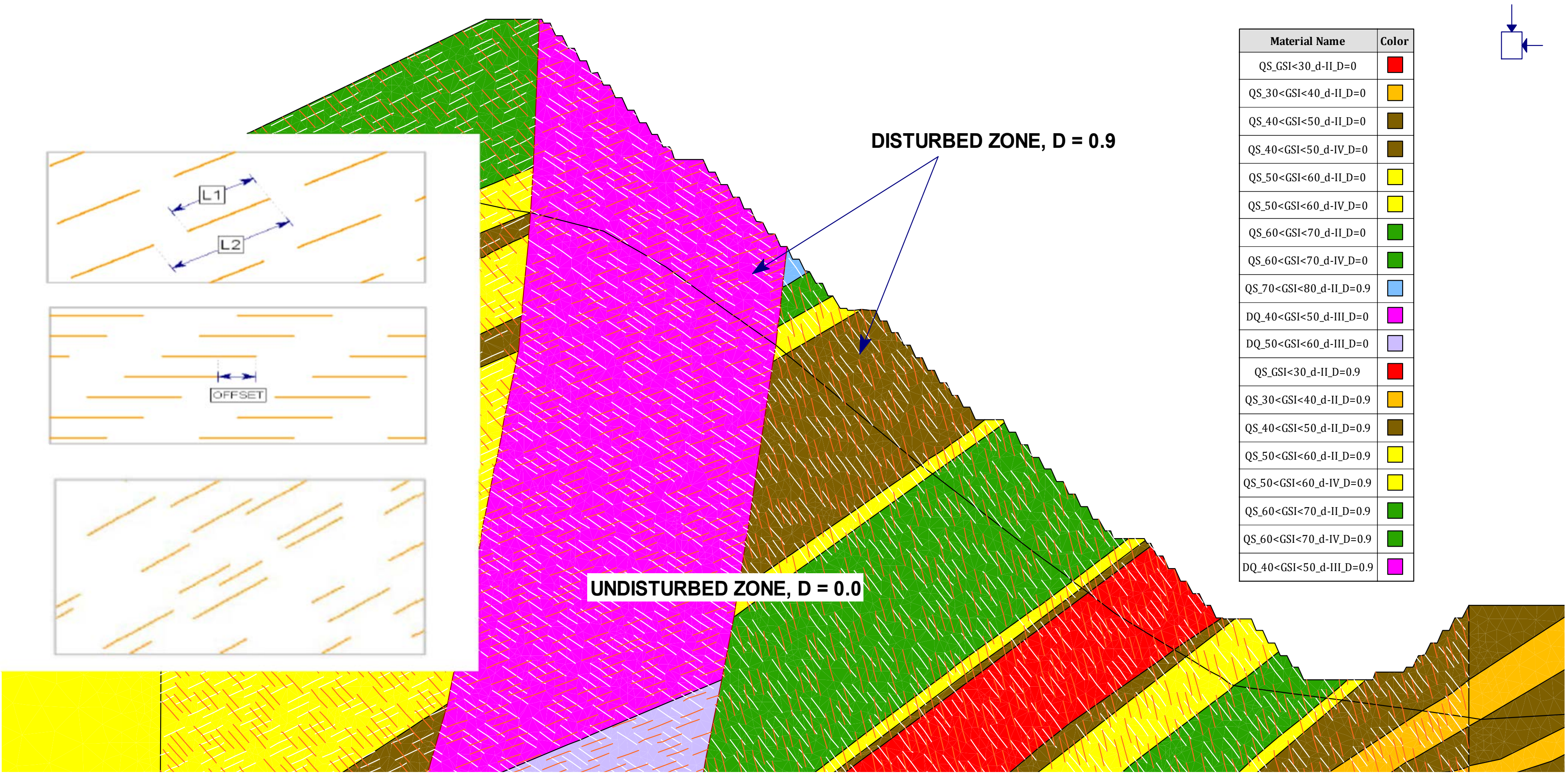
Example of Limit Equilibrium Method (GLE)

Interramp and Overall Stability Analysis



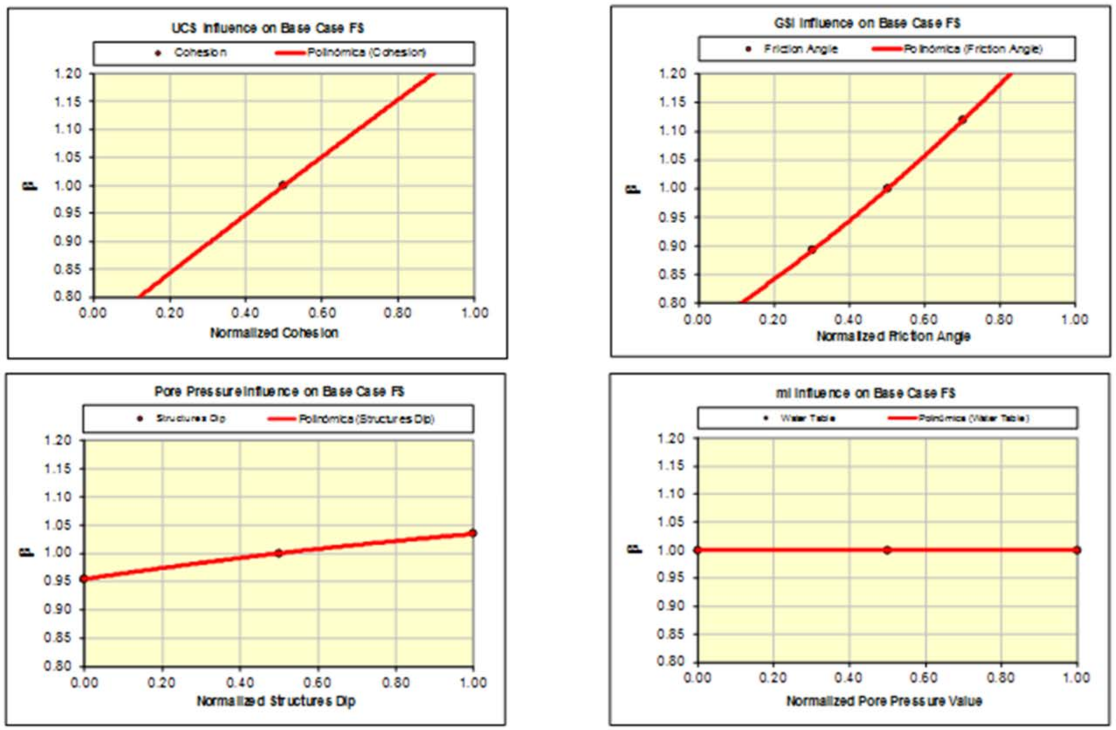
Montecarlo simulation for calculated the FoS

Interramp and Overall Stability Analysis

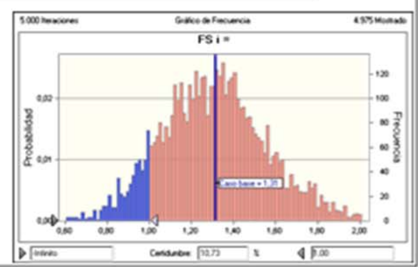


Example of 2D Numerical Modelling Analysis.

Surface Response Method



$$FS_i = FS_{caso\_base} \cdot \beta^1 \cdot \beta^2 \cdot \beta^3 \cdot \beta^4$$

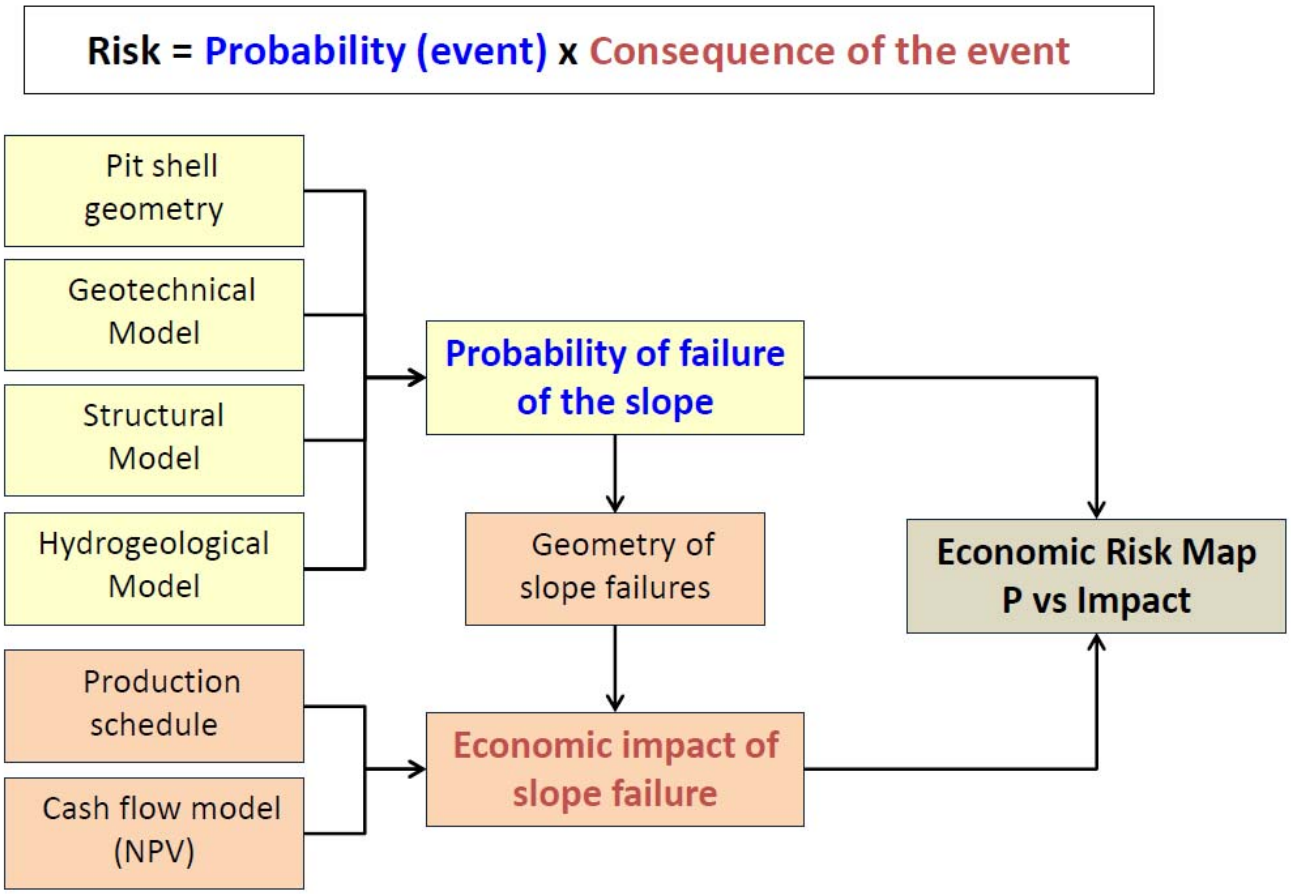


Acceptability Criteria

Slope Scale	Consequences of Failure	Acceptability Criteria		
		Factor of Safety [FOS]	Factor of Safety [FOS]	Probability of Failure
		(min)	(min)	(max)
		(Static)	(Pseudo-static)	P[FOS≤1]
Bench	Low - High	1.1	N/A	25 - 50%
Inter-ramp	Low	1.15 - 1.2	1.0	25%
	Medium	**1.2**	**1.0**	**20%**
	High	1.2 - 1.3	1.1	10%
Overall	Low	1.2 - 1.3	1.0	15 - 20%
	Medium	**1.3**	**1.1**	**10%**
	High	1.3 - 1.5	1.1	5%

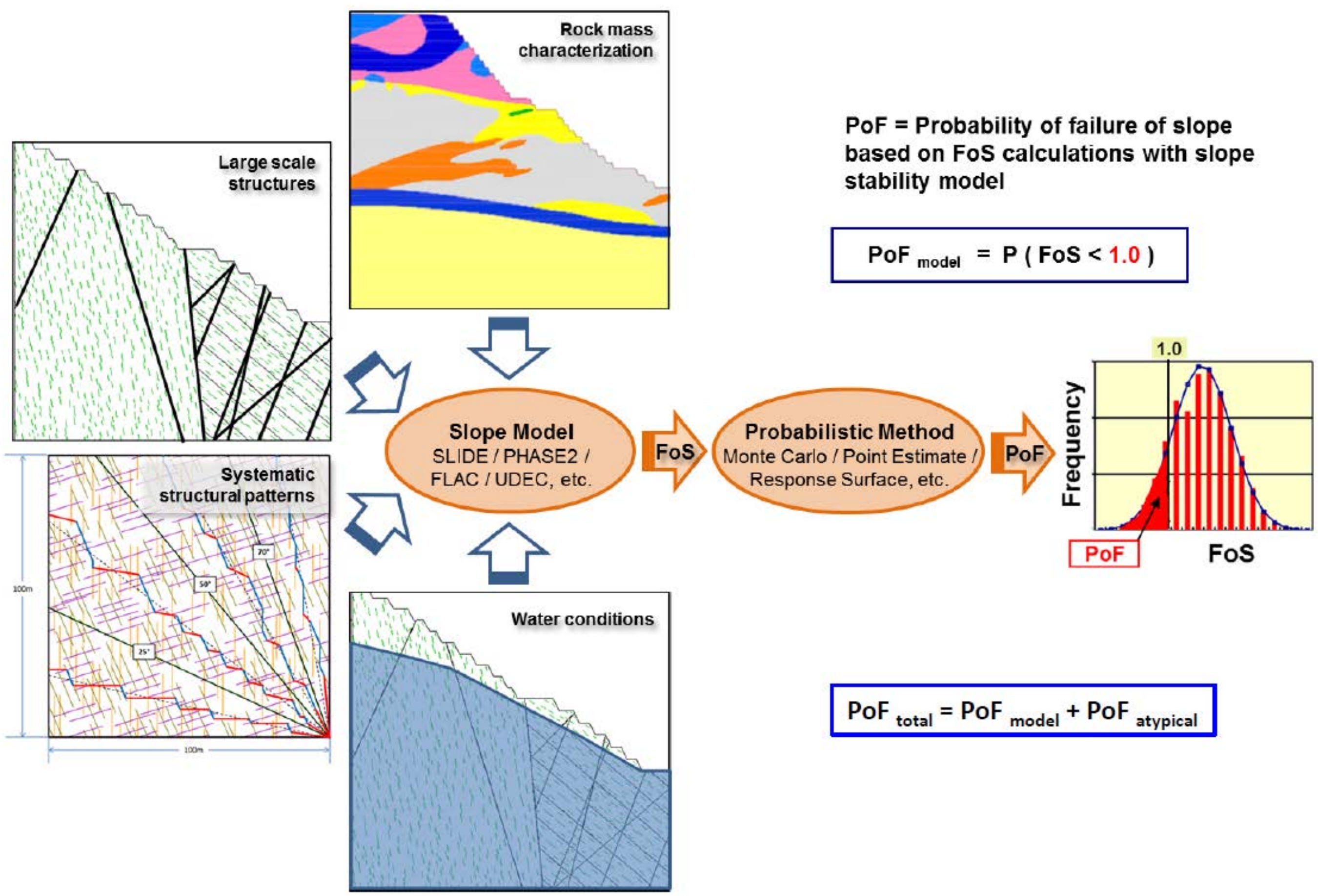
READ & STACEY (2009): "GUIDELINES FOR OPEN PIT SLOPE DESIGN".

Risk-based Slope Design Approach



Risk Based Slope Design, Contreras, L.F. (SRK, 2013)

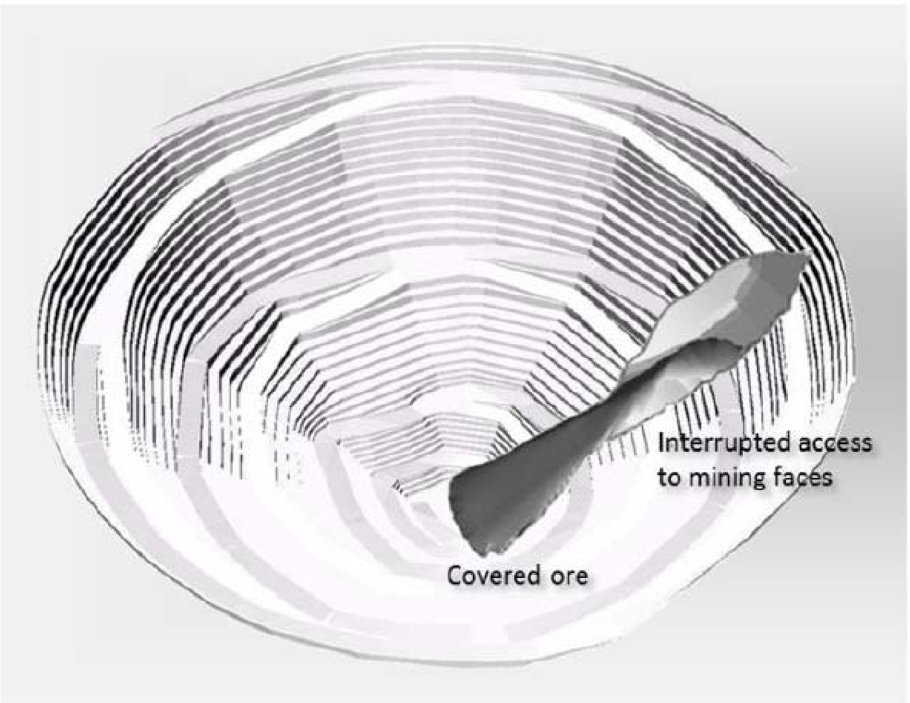
Concept of Probability of Failure of the Slope

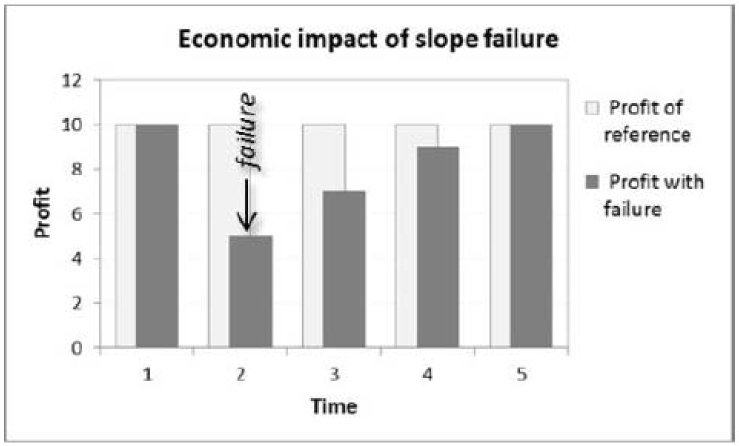


Risk Based Slope Design, Contreras, L.F. (SRK, 2013)

Interramp & Overall Slope Design

Conceptual Basis for estimation of the economic impact of slope failure





Slope Failure Impacts:

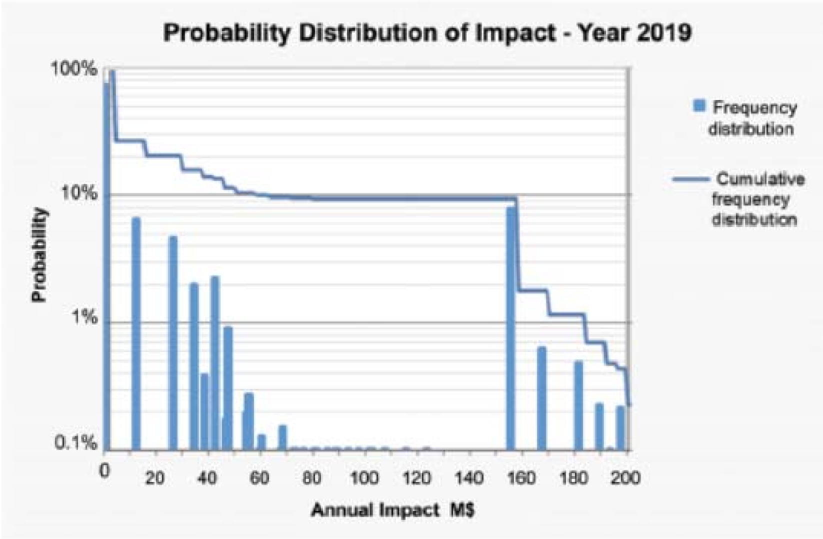
- Disruption of planned ore feed to plant.

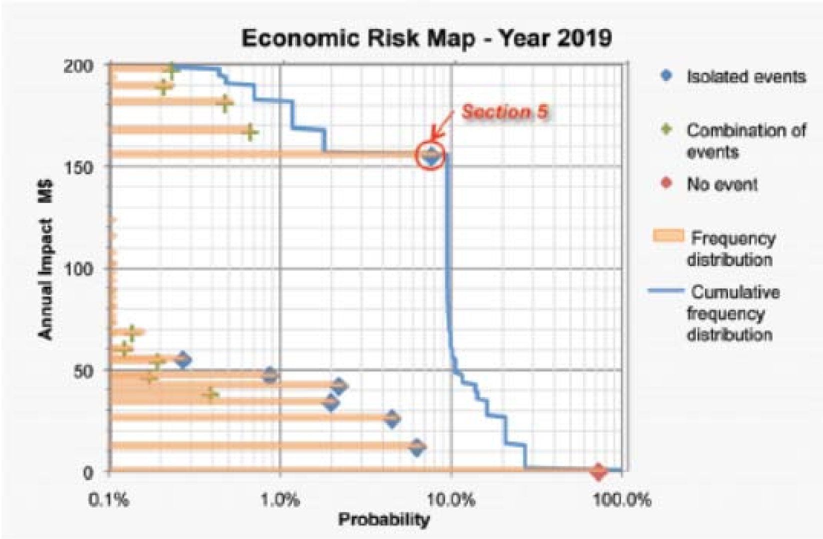
- Additional costs to restore site.

Failure Impact = $NPV_{reference} - NPV_{with\ failure}$

The Economic Risk Map as a Tool for Pit Slope Optimization, Contreras, L.F. (SRK, 2015)

Final Comments





Example of Construction of the economic risk envelope for year 2019. a) Probability distribution graphs. b) risk map result.

An Economic Risk evaluation approach for pit slope optimization, Contreras, L.F. (2015)

Risk Acceptability Matrix for Economic Impact

	Level	Range M$	Risk Category				
Impact	5	> 200	H	H	H	H	H
	4	100 - 200	M	M	H	H	H
	3	50 - 100	L	M	M	M	H
	2	10 - 50	L	L	L	M	M
	1	< 10	L	L	L	L	L
		Range %	<10%	10-20%	20-50%	50-80%	>80%
		Level	1	2	3	4	5
		Likelihood					

An Economic Risk evaluation approach for pit slope optimization, Contreras, L.F. (2015)

Economic Risk Map Example