Improved stope design guidelines based on Stability Graph Method for Swedish underground mines (ISDG)

Project leader
Yang Zou, Ping Zhang, LTU

Partners
LTU, Boliden, Zinkgruvan

Project duration
Jan 2024 – Oct 2025

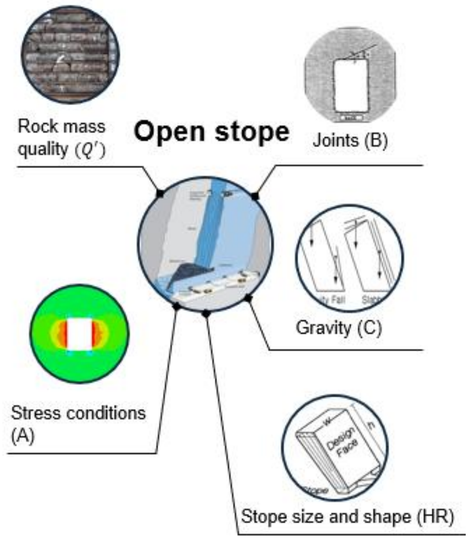
SWEDISH MINING INNOVATION

Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Background

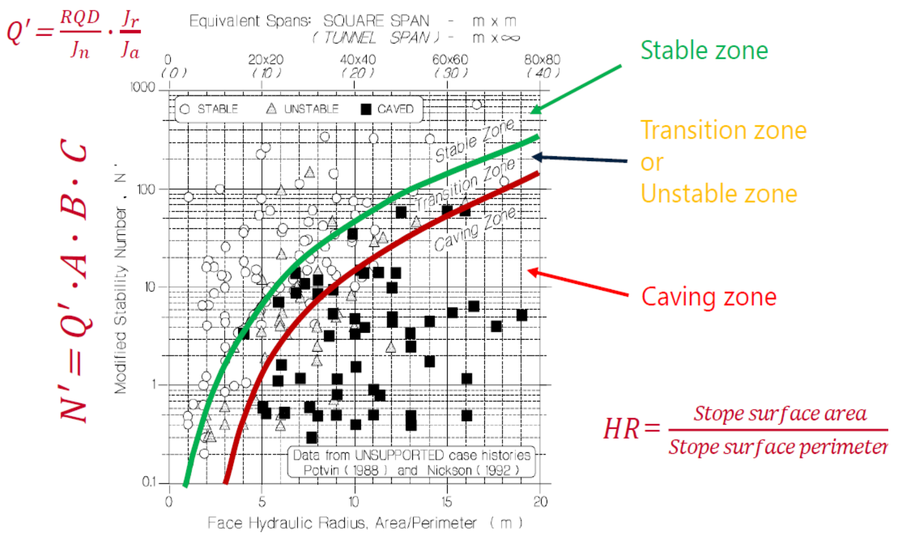
- Stability graph method (SGM) is an empirical method for dimensioning open rooms/stopes and support design based on Q' and other three factors.
  - -An empirical method based on Q-system
  - -For initial dimensioning and support design for open stopes
  - -Developed in 1981 (Mathews et al., 1981)
  - -Modified in 1988 by Potvin and called Modified Stability Graph Method

- **Site specific conditions**
- **Uncertainties in data and analysis**



$$Q' = \frac{RQD}{J_n} \cdot \frac{J_r}{J_a}$$

$$N' = Q' \cdot A \cdot B \cdot C$$

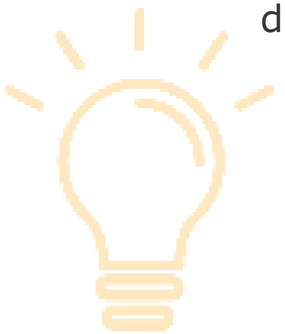


$$HR = \frac{Stope\ surface\ area}{Stope\ surface\ perimeter}$$

Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Goals of the project

- Improve the data collection approach for assessing stope stability with focuses on applying advanced scanning technology and selecting critical input parameters;
- Calibrate the three-dimensional numerical modelling methodology developed from previous pre-study project to reconcile observation;
- Examine the feasibility of using machine learning techniques to predict open stopes' stability using data from on-site cases and numerical models;
- Develop guidelines for qualitative and quantitative collection of input parameters used in stope design; and
- Develop new stope design tools/guidelines to reduce dilution and waste rock with the aid of numerical modelling and machine learning techniques based on on-site collection of cases and case histories from different rock masses in Swedish underground mines.

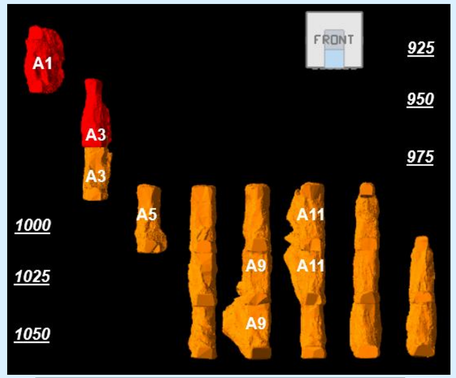


Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

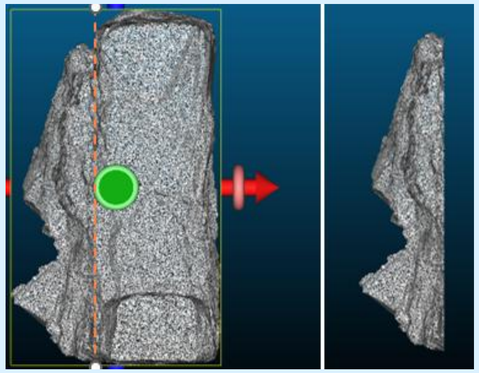
Results so far

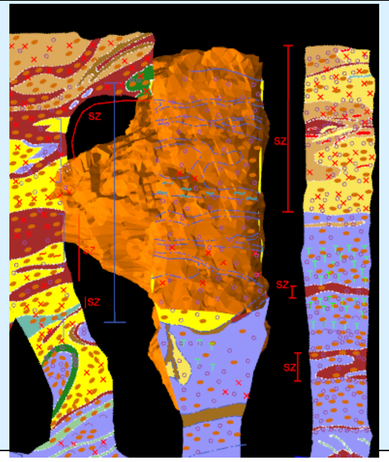
- Improve the data collection approach

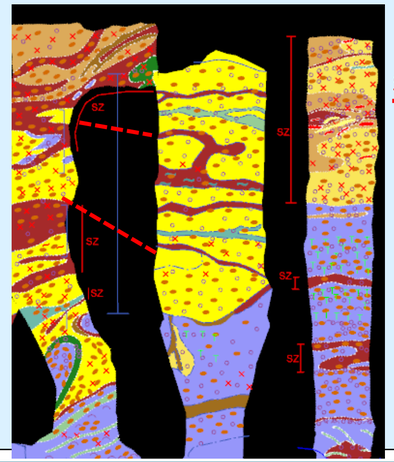
Deswik



Cloud points



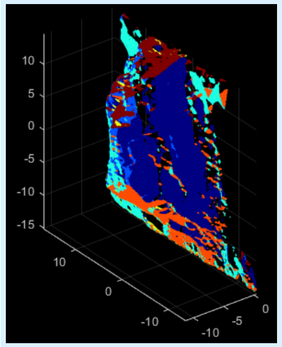


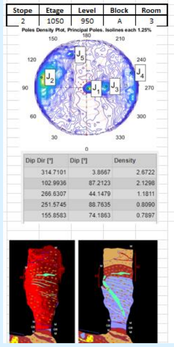


Data sources

Data Extractors

Discontinuities set extractor

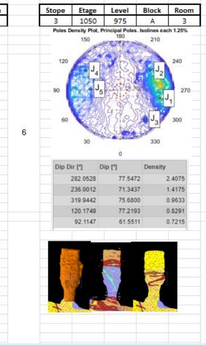




Stope	Etage	Level	Block	Room
2	1050	950	A	3

Poles Density Plot, Principal Poles. Isolines each 1.25%

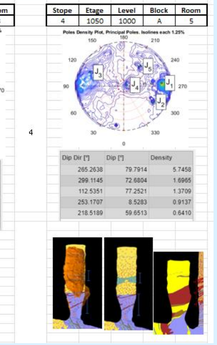
Dip Dir [°]	Dip [°]	Density
314.7101	3.8667	2.6722
102.9936	87.2123	2.1298
286.6307	44.1479	1.1811
251.5745	88.7635	0.8090
155.8583	74.1863	0.7897



Stope	Etage	Level	Block	Room
3	1050	975	A	3

Poles Density Plot, Principal Poles. Isolines each 1.25%

Dip Dir [°]	Dip [°]	Density
282.0528	77.5472	2.4075
236.0012	71.3437	1.4175
319.9442	75.6800	0.9633
120.1749	77.2193	0.8291
92.1147	61.5511	0.7215

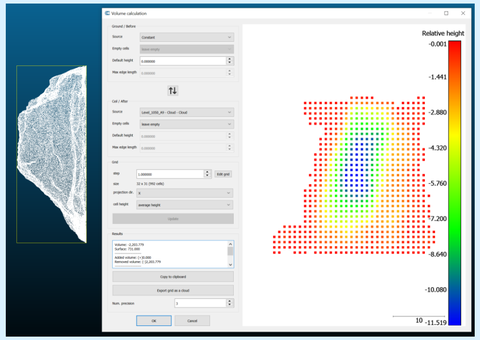


Stope	Etage	Level	Block	Room
4	1050	1000	A	5

Poles Density Plot, Principal Poles. Isolines each 1.25%

Dip Dir [°]	Dip [°]	Density
265.2638	79.7914	5.7458
299.1145	72.8804	1.6966
112.5351	77.2521	1.3709
253.1707	8.5283	0.9137
218.5189	59.6513	0.6410

Overbreak calculator



Geological information extractor

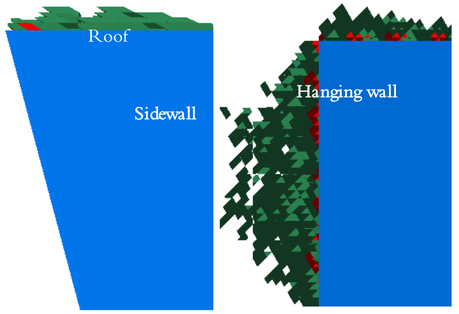
Level	925	950	975	1000	1000	1025	1025	1050
Room	A1	A3	A3	A5	A11	A9	A11	A9
Dolomite	24.41	46.16	24.21	7.81	62.51	41.28	62.79	8.70
Kvartsit	26.17	0.00	0.00	0.00	0.00	0.00	4.18	0.00
Chert/Kvarsiter (16)	15.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Glimmerkvartsit (148)	0.00	18.95	31.61	32.69	6.68	33.16	7.68	67.28
Flogopitkvartsit (202)	0.00	5.98	12.28	39.61	4.52	0.84	16.70	0.84
Sericitikvartsit (106)	1.88	11.26	16.24	0.00	13.40	0.00	0.00	0.00
Talkskiffer (152)	0.00	3.75	0.00	2.58	0.00	1.81	0.00	3.38
Flogopitskiffer (200)	27.41	8.47	9.69	14.09	7.00	14.50	8.65	18.01
Skarn (109)	0.00	0.00	0.00	0.00	2.35	0.00	0.00	0.00
Massiva sulfider (170)	4.53	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Semi massiva sulfider (307)	0.00	0.00	2.50	3.22	0.00	7.22	0.00	0.60
Diabas (132)	0.00	3.03	3.48	0.00	0.00	0.00	0.00	0.00
Tremolitskarn (181)	0.00	2.39	0.00	0.00	3.53	1.18	0.00	1.18
Kalkstensbreccia (190)	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

1000	1000	1000	1025	1025	1025	1050	1050	1050	1050
A7	A9	A13	A7	A13	A15	A7	A11	A13	A15
29.68	53.10	63.57	18.79	53.91	33.18	3.70	35.79	41.72	17.50
0.00	0.00	0.00	0.00	0.00	0.00	0.00	4.18	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
34.30	1.15	12.68	42.96	23.79	15.13	28.36	34.52	18.46	49.92
13.73	0.00	0.00	5.62	1.07	6.19	18.50	16.70	1.07	4.06
0.00	2.76	5.92	0.00	0.00	13.87	2.73	0.00	8.83	0.00
0.60	3.52	0.00	0.60	0.00	0.00	1.49	0.00	0.00	0.00
16.93	27.21	15.71	28.66	18.71	19.00	44.44	7.73	27.40	22.79
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.34	0.00	0.00	0.00
0.00	11.61	1.11	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4.76	0.65	1.02	3.37	2.53	6.24	0.45	1.08	2.53	5.72
0.00	0.00	0.00	0.00	0.00	6.41	0.00	0.00	0.00	0.00
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

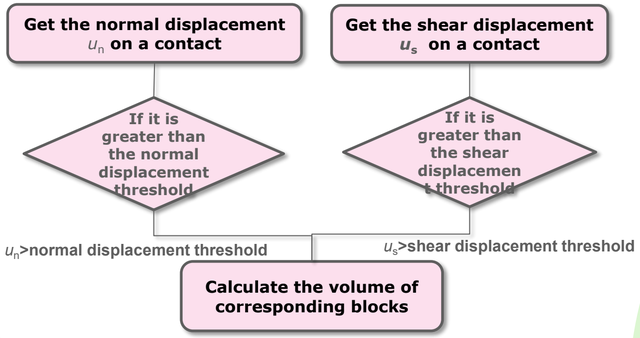
Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Results so far

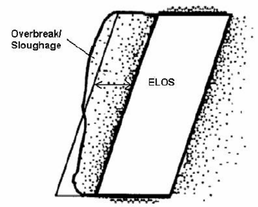
- Calibrate the three-dimensional numerical modelling methodology



Detached zoned in numerical models



$$ELOS = \frac{Volume\ of\ detached\ blocks}{Area\ of\ Face}$$

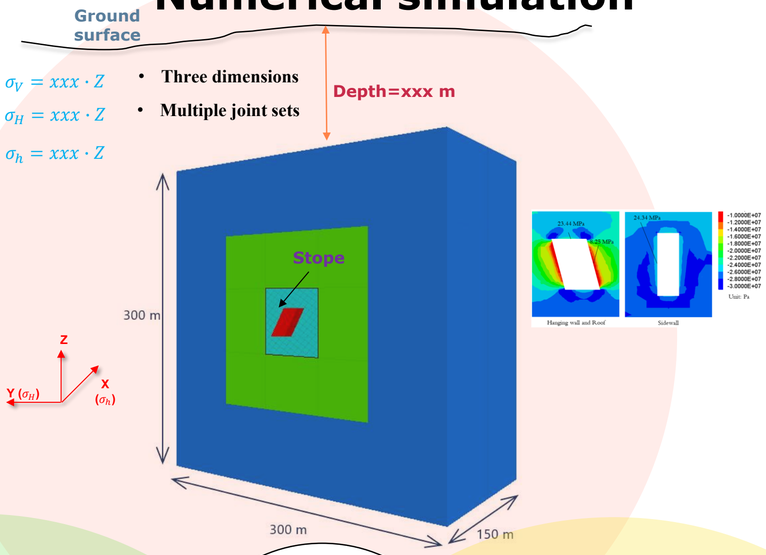


Displacement criteria

Normal Threshold: 2 mm

Shear Threshold: 9 mm

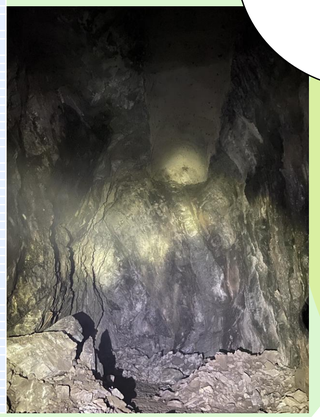
Numerical simulation



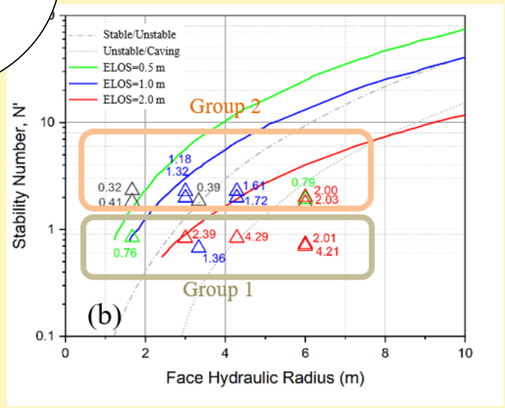
ELOS: equivalent linear overbreak/slough

Field data

	Data collection on site		
Data speficied	Listed items	Parameters for the analysis	Values
Geological information			
	Core logging	RQD	
	Joint sets	Jn	
	Joint orientation		
		Dip direction	
		Dip angle	
	Joint surface condition		
	1. Roughness	Jr	
	2. Alternation	Ja	
Rock types and properties			
	Rock types		
	Rock strength	UCS	
Stope geometry			
	Stope dimension		
		Height	
		Length	
		Width	
	Stope orientation		
		Dip direction	
		Dip angle	
Stress condition			
	Stress measurement data		
	Numerical modelling results		
Stope status			
		Stable	
		Unstable	
		Caving	
Cavity scanning			
	Overbreak/underbreak	ELOS	
Others			
	Mining method		
	Mining sequence		



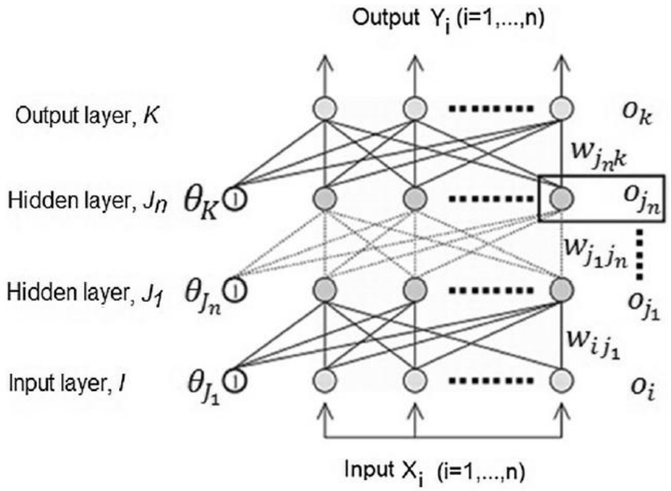
Empirical method (SGM)



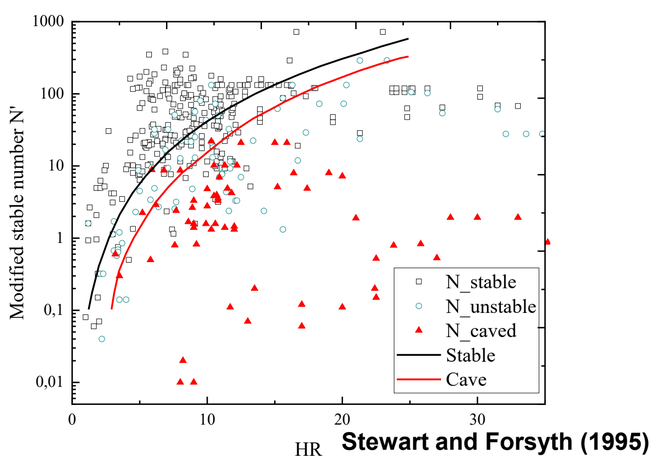
Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Results so far

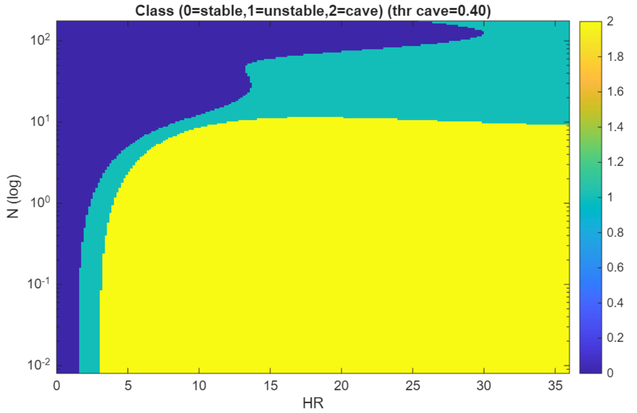
- Examine the feasibility of using machine learning techniques

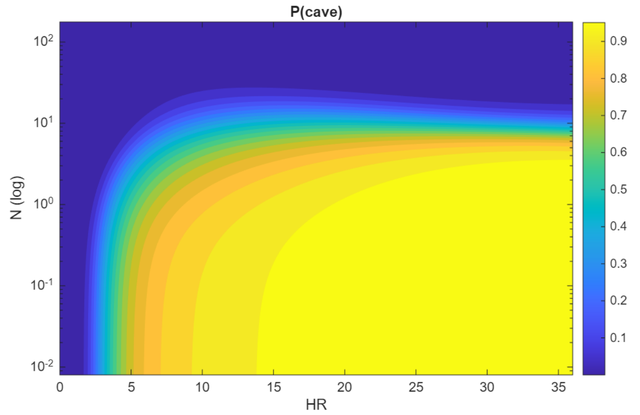


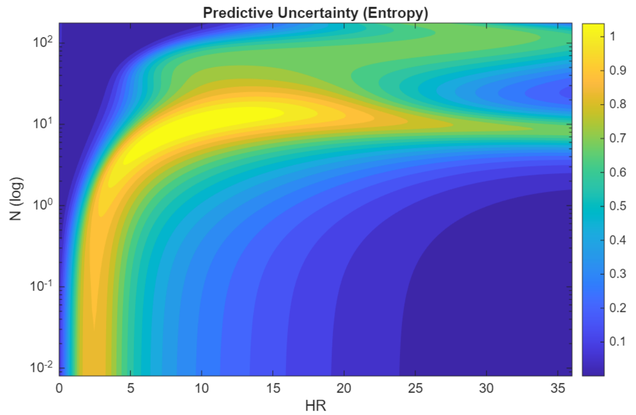
A feed-forward neural network (FFNN) classifier



Stewart and Forsyth (1995)







Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

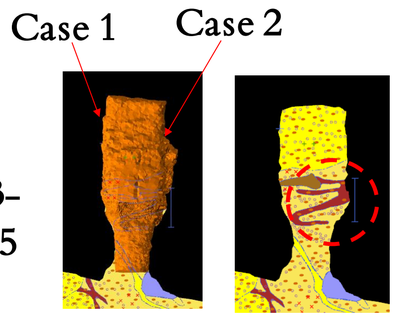
Results so far

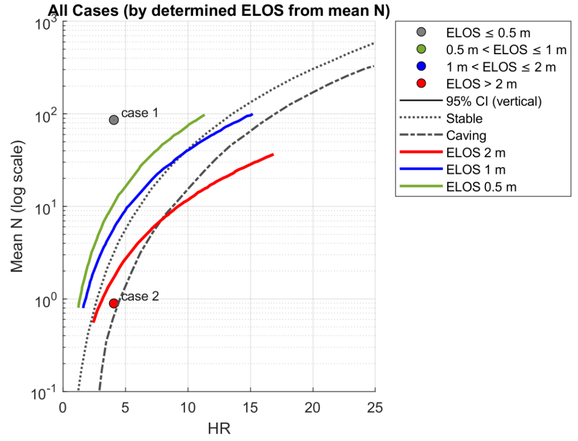
- Mechanism analysis

➢ Joint set / foliation - *Appearance*

Case	muRQD	sigmaRQD	Jn	Jr	Ja	muUCS	sigmaUCS	stress	B	C	rho	width	height	alpha_deg	OS_measu
1	65.6923	1.41421	0.5	3	1	77	28	33.8	0.442581	3.176514	0	14.814	18.016	90	2.363825
2	65.6923	1.41421	6	1.5	4	77	28	33.8	0.442581	3.176514	0	14.814	18.016	90	2.363825

A3-975

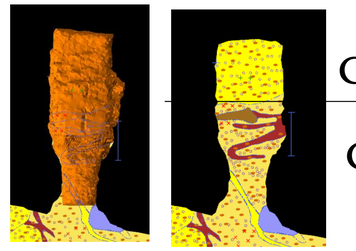


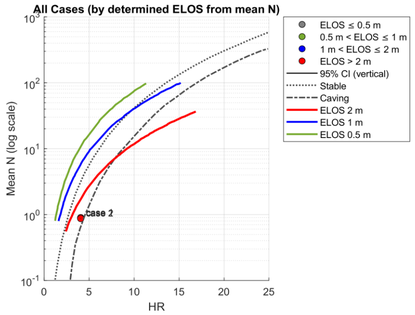


➢ UCS & RQD

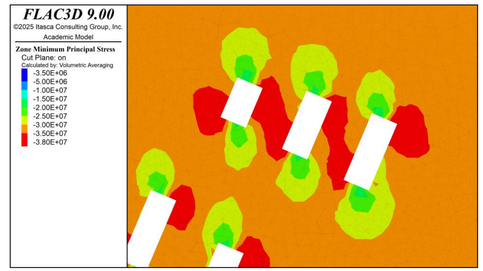
Case	muRQD	sigmaRQD	Jn	Jr	Ja	muUCS	sigmaUCS	stress	B	C	rho	width	height	alpha_deg	ELOS_measure
1	77.8641	12.4645	9	0.5	10	77	28	40.1	0.208	4.072272	0	16.258	18.564	90	10.74219964
2	65.6923	1.41421	9	0.5	10	169	39	40.1	0.208	4.072272	0	16.258	18.564	90	10.74219964

A3-975

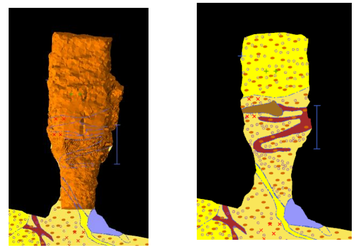


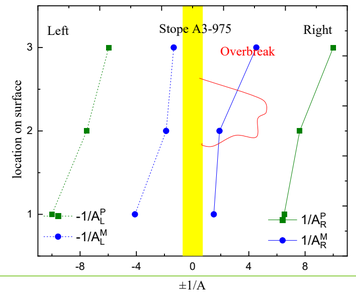


➢ Stress orientation/discrepancy



A3-975

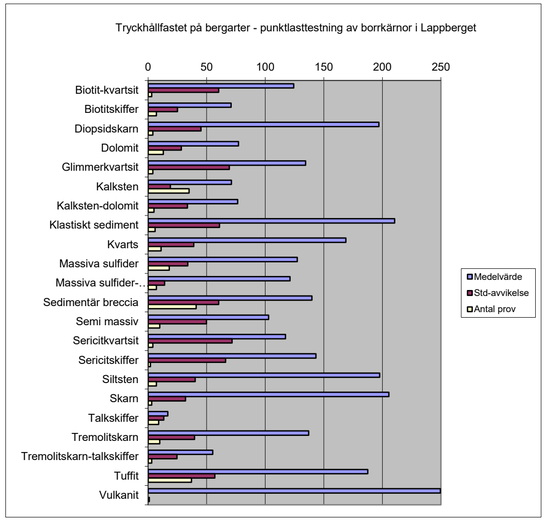




Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Results so far

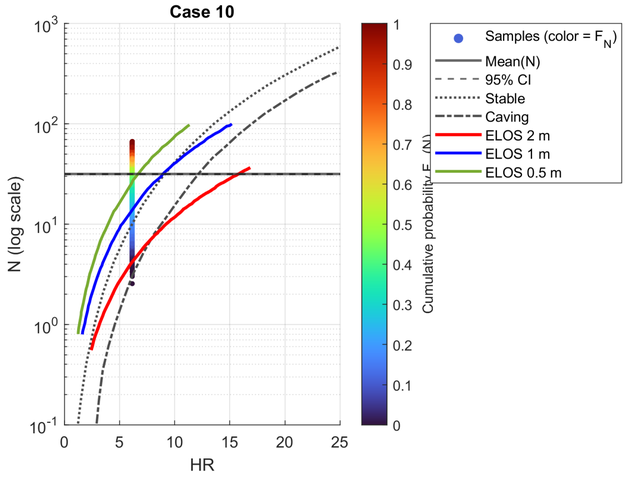
- Develop new stope design tools & data collection guidelines

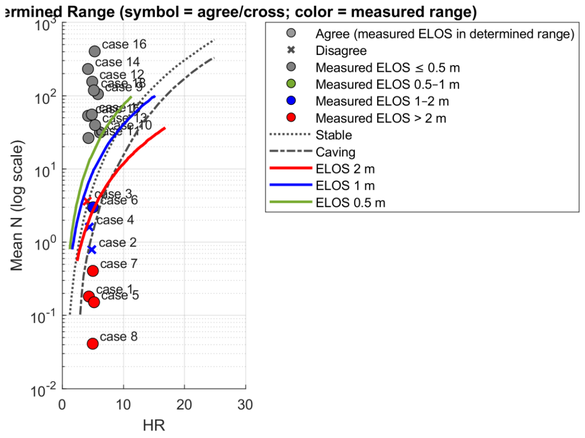


Name	Count	Length	Mean	Std. dev.	Coeff. var.	Variance	Minimum	L. quartile	Median	U. quartile	Maximum
DOLOMITE	60	294.3									
BRQD	60	294.3	77.8641	12.4645	0.160081	155.365	0	77	80	83	91
RMR	60	294.3	77.1033	6.87274	0.0891368	47.2346	31	72	77	82	87
LIMESTONE	31	110.3									
BRQD	31	110.3	76.4193	9.28679	0.121524	86.2445	0	73	78	81	91
RMR	31	110.3	76.3309	6.5648	0.0860045	43.0966	37	77	77	82	87
QUARTZITE (SEDIMENTARY)	2	5.2									
BRQD	2	5.2	65.6923	1.41421	0.0215278	2	65	65	65	67	67
RMR	2	5.2	73.9615	2.12132	0.0286814	4.5	72	72	75	75	75
SERICITE QUARTZITE	0	0.0									
BRQD	0	0.0									
RMR	0	0.0									

Probabilistic SGM (PSGM) development based on Monte Carlo method

Case	HR	ELOS_measured	Determined_Range	Measured_Range	Agree	Stable_Prob	Transition_Prob	Caving_Prob	ELOS_le_0_5m_Prob	ELOS_0_5_to_1m_Prob	ELOS_1m_to_2m_Prob	ELOS_gt_2m_Prob	MeanN	StdN
1	4.333661364	10.74219964	>2 m	>2 m	TRUE	0	0	1	0	0	0	1	0.076172417	0.042106832
2	4.800650325	1.604231289	>2 m	1–2 m	FALSE	0	0	1	0	0	0	1	0.23406639	0.101711499
3	4.064712519	2.363825198	>2 m	>2 m	TRUE	0.00044	0.81437	0.18519	0	0	0.10984	0.89016	1.057743113	0.476125041
4	4.396137199	1.245381973	>2 m	1–2 m	FALSE	0	0.03877	0.96123	0	0	0	1	0.477294517	0.184801323
5	5.182855152	3.289380985	>2 m	>2 m	TRUE	0	0	1	0	0	0	1	0.044817101	0.021508196
6	5.015481956	1.418240582	>2 m	1–2 m	FALSE	0	0.92664	0.07336	0	0	0.39777	0.60223	2.577433999	0.766480967
7	4.987396202	3.377730446	>2 m	>2 m	TRUE	0	0	1	0	0	0	1	0.119471366	0.052551181
8	4.964588836	5.551798493	>2 m	>2 m	TRUE	0	0	1	0	0	0	1	0.024298178	0.01350982
9	5.812656718	0.236464889	≤0.5 m	≤0.5 m	TRUE	1	0	0	0.99984	0.00016	0	0	168.3934977	54.92861512
10	6.142765041	0.095304901	1–2 m	≤0.5 m	FALSE	0.31962	0.67868	0.0017	0.00198	0.13203	0.82576	0.04023	9.295215847	4.447147934
11	4.262991931	0.275220242	0.5–1 m	≤0.5 m	FALSE	0.99661	0.00339	0	0.13364	0.51344	0.35292	0	8.265217662	3.283764572
12	4.885447953	0.293722056	≤0.5 m	≤0.5 m	TRUE	1	0	0	1	0	0	0	218.2868509	62.65269809
13	5.353025903	0.269193978	0.5–1 m	≤0.5 m	FALSE	0.88449	0.11551	0	0.08585	0.35257	0.56153	0.00005	11.65393564	5.137384995
14	4.188744176	0.233230268	≤0.5 m	≤0.5 m	TRUE	1	0	0	0.99999	0.00001	0	0	135.6717626	89.57144708
15	4.206634639	0.214692487	≤0.5 m	≤0.5 m	TRUE	1	0	0	0.99419	0.00581	0	0	45.84513599	13.62486077
16	5.286591249	0.262418344	≤0.5 m	≤0.5 m	TRUE	1	0	0	1	0	0	0	534.9827223	153.7668645
17	4.81724912	0.145899459	≤0.5 m	≤0.5 m	TRUE	0.99952	0.00048	0	0.41347	0.53441	0.05212	0	16.1029609	7.277835068
18	5.152143177	0.410447493	≤0.5 m	≤0.5 m	TRUE	1	0	0	1	0	0	0	122.9117642	35.89530351





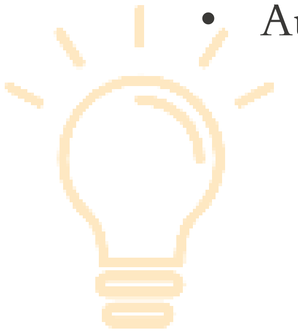
Summary and Further studies

❑ **Summary**

- Data collection improvement
- Numerical model calibration methods
- Application of machine learning technique in SGM
- New stope design tools/guidelines development (PSGM)

❑ **Further studies**

- Standardization in data collection - *Documentation*
- Automatization and in data collection – *Development and Integration of Image/AI based method*
- Automatization in data calculation and analysis - *MATLAB application development*



Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program

Mining innovation for a sustainable future

SWEDISH MINING INNOVATION

Med stöd från
VINNOVA Sveriges innovationsmyndighet
Energimyndigheten
FORMAS
Strategiska innovations-program