AngloAmerican

Geotechnical design work for water reservoir stopes at Venetia Underground Mine

Jeanne Walls
Principal Geotechnical Engineer

June 2023

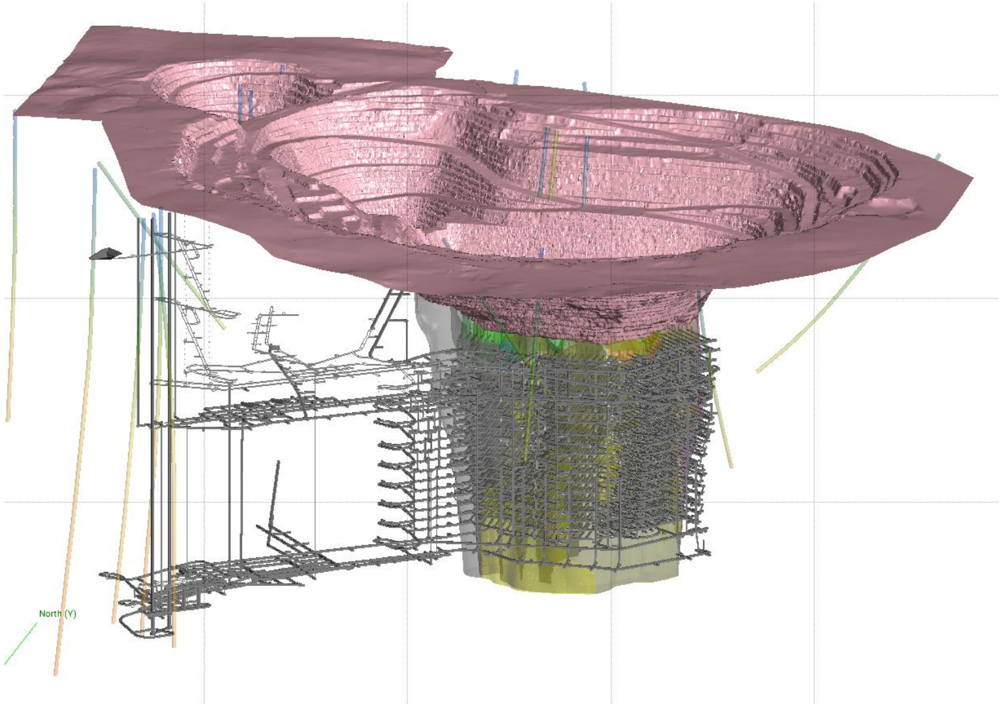
Context

- Management of rainwater ingress in SLC below open pit requires robust measures to arrest, store, and release flood water in a safe and controlled manner
- Water reservoir stopes were proposed to improve the response capacity for large volume water ingress
- Existing approach utilises flood control doors however the engineering, construction and management of these structures introduces risk elements that may be offset with the introduction of water reservoir stopes
- Rock mass response within the walls and crown of the WRS affects longevity and reliability of the stopes.
- Simple geotechnical assessment was carried out to evaluate the expected rock mass response, effects of instability, and measures required to ensure stability

Source: Venetia Underground Mine – Evolution of VUP Flood Control

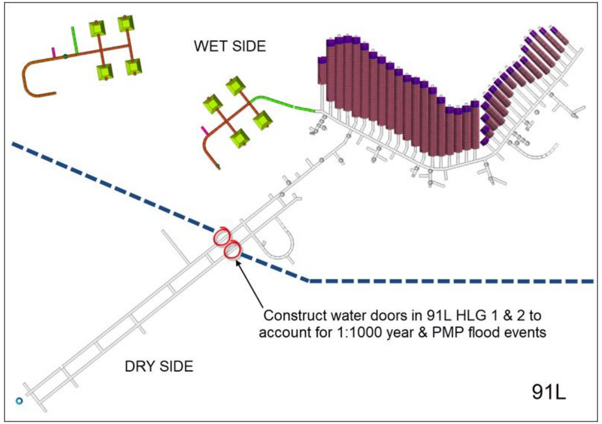
Water Ingress Source Management

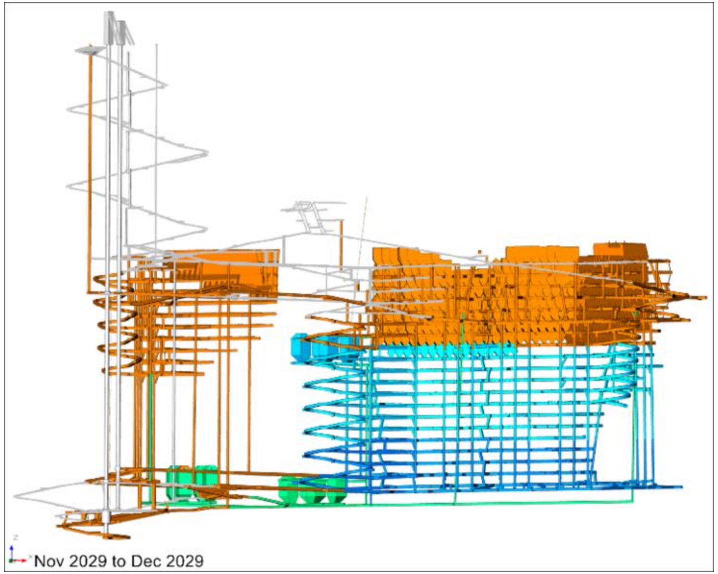
- Rainwater events can generate underground flooding conditions due to ingress through pit walls, pit floor, drill holes, surface portal
- Underground workings separated into "wet side" and "dry side" for inundation risk management
- Typically, measures cater for 1:100 or 1: 1000 ingress events. However, seasonal rainfall events present sufficient disruption to underground operations to warrant focused management strategies
- Day to day pumping arrangements cannot arrest or remove inundation risk without additional measures



Flood Control Strategy

- Integrated system of flood doors to contain UG flood water within the production ("wet") zone
- Diversion of large volumes of water to UG water reservoirs (WRS)
- Extreme events may flood parts of lower mine workings (water pass feed from ToM to BoM) with protection of dry areas by high-head flood doors





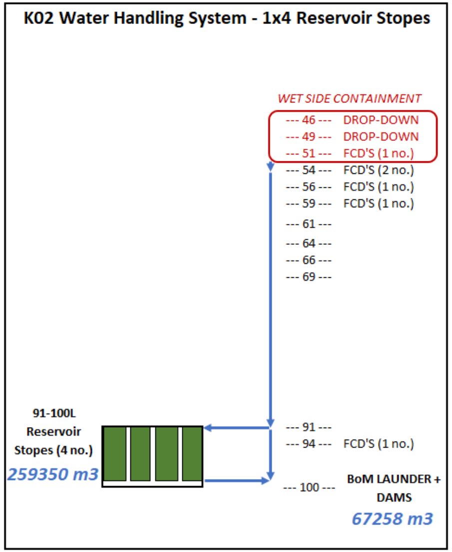
Flood Water Volume Expectations

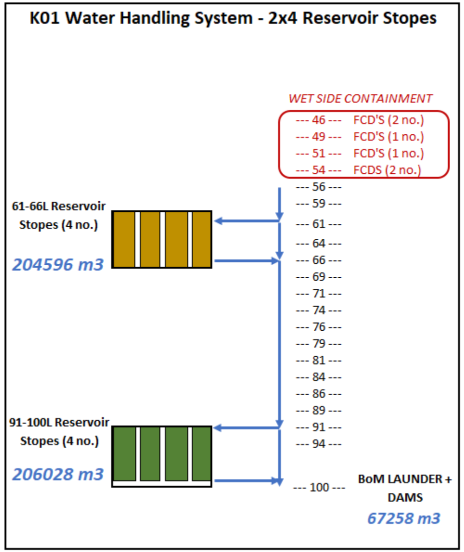
- WRS therefore provide a rapid surge capacity to activate evacuation measures and engage water retention doors

K01 Peak Modelled Stormwater Inflows - Pumping (4,000m^3/hr)

Duration (hr)	0.5	1	3	6	12	24	72	168
units	m^3							
1:2 year		6,310	16,820	37,590	780			
1:5 year								
1:10 year						796		
1:20 year	12,930	41,160	69,350	88,300	80,300	34,348		
1:50 year	21,860	56,050	90,500	112,900	112,100	62,936	26,364	
1:200 year	38,930	82,400	127,100	155,900	159,900	62,936	157,589	
1:500 year	51,700	101,000	152,000	186,200	192,700			
1:1000 year						195,091	516,107	1,027,000
PMP	266,100	453,600	714,900	996,000	1,242,000	1,824,000	1,558,688	2,377,000

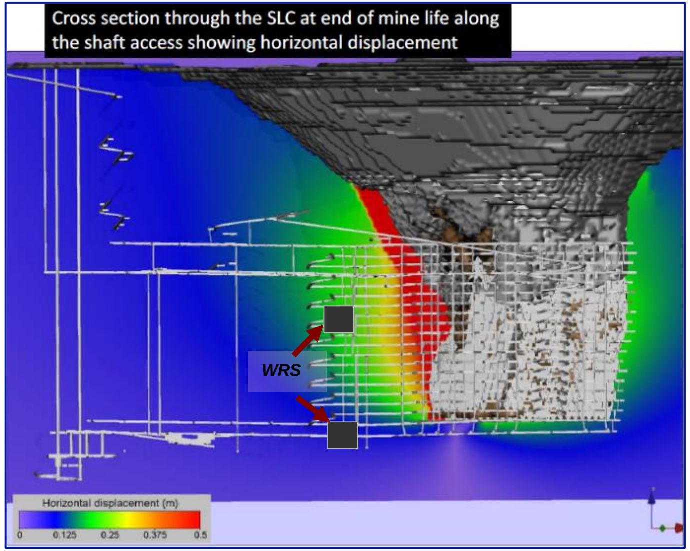
K02 Lower	Height (overall, inclusive of crown), m	77.0
K01 Lower	Height (overall, inclusive of crown), m	60.0
K01 Upper	Height (overall, inclusive of crown), m	61.5
All WRS clusters	Width and Length (square), m	30
	Spacing (adjacent), m	30
	Spacing (opposite), m	60
	Crown height, m	10



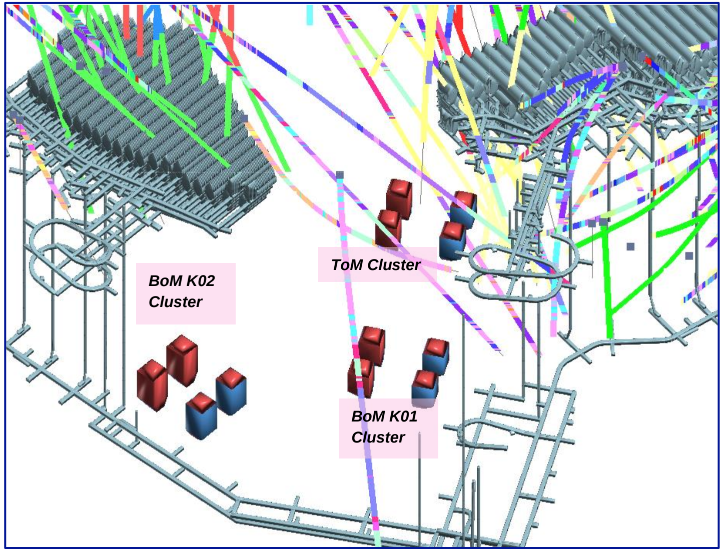


WRS Placement and Data Availability

- LoM stability : mining stress induced deformation



- Drill hole piercing



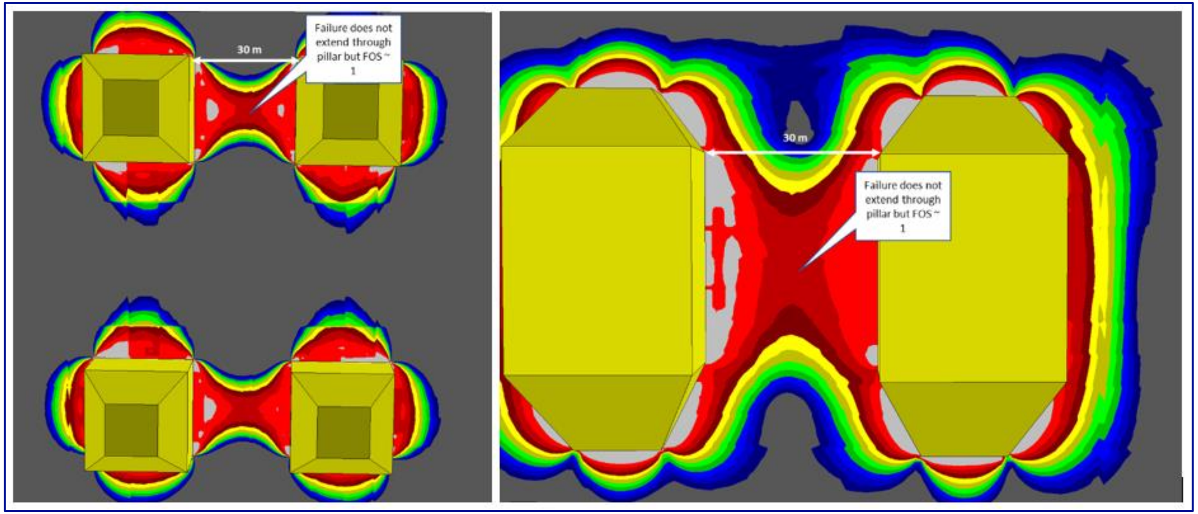
Rock Mass Characterisation

Data sources : Drillhole data (historic, <2011); Extrapolated mapping data (ToM – decline, access drives, BoM)

Rock Type	Statistic	UCS (MPa)	UTB (MPa)	Density (10^3 kg.m^{-3})	Internal friction angle, ϕ (°)	Cohesion, Co (kPa)	Base friction angle, ϕ_b (°)	RMR	Q	GSI	m_b	m_i	s (Hoek-Brown)	a (Hoek-Brown)	Young's Modulus, E (GPa)	Poisson's Ratio, v
Dolerite	Mean	210		2.93	37	6.7	44	69	-	-	-	-	-	-	82.5	0.26
	Stdev	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Metaseds	Mean	130 - 150	10	2.90	41	1.9	36	61	4 - 10	-	2.2	-	0.015	-	81.4	0.27
	Stdev	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Marble	Mean	129	10	2.84	41	77.5	30	79	46	72	5.7	15.6	0.045	0.5	85.0	0.35
	Stdev	23	-	0.16	-	-	-	5	4	-	-	-	-	-	12.5	0.06

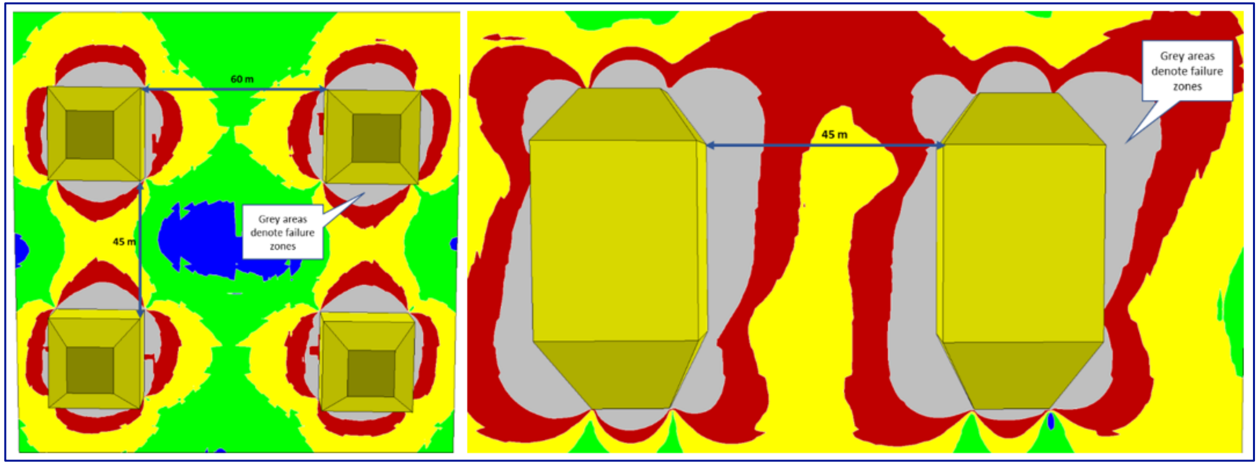
Joint Set	J1		J2		J3			J4		Foliation		
Component	Dip (°)	Dip Direction (°)	Dip (°)	Dip Direction (°)	Dip (°)	Dip Direction (°)	Spacing, m	Dip (°)	Dip Direction (°)	Dip (°)	Dip Direction (°)	Spacing, m
Dolerite	59	150	50	330	70	228	-	80	024	-	-	-
Metaseds	74	139	20 - 55	015 - 030	73	208	0.8	8	009	60	050	0.6
Marble	44	246	56	106	-	-	-	-	-	89	032	-

Interactive Stress Effects to Assess Spacing : ToM



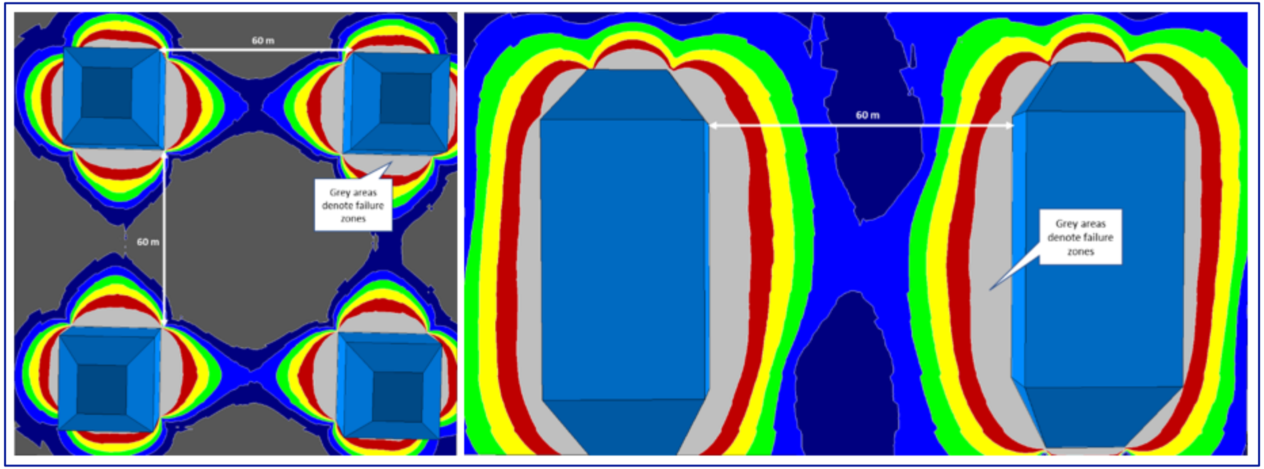
- Map3D elastic model to test offsets and interactive stress (HB criterion); k = 1.5; Metaseds
- ToM WRS situated at ≈550m dbs (550m – 600m)
- Stress induced failure envelope provides indicative extent of tensile zone to estimate limit of clamping for kinematic failure effects
- At 30m spacing, limit of FoS
- Revised spacing tested at 45m

Interactive Stress Effects to Assess Spacing : ToM



- At 45m offset there continues to exist stress interaction with FoS > 1.0 in middling; indicative arching effect from crown to crown : implies ground support for crown stability required.
- ToM WRS longevity <5 years
- Depth of failure ≈10m-12m

Interactive Stress Effects to Assess Spacing : BoM



- At 60m offset there continues to exist stress interaction with FoS > 1.0 in middling.
- BoM WRS longevity >25 years (LoM)
- Depth of failure ≈10m-12m : probable middling reduction over time by 20-25m, resulting in a remainder 35m-40m
- What constitutes tolerable instability?

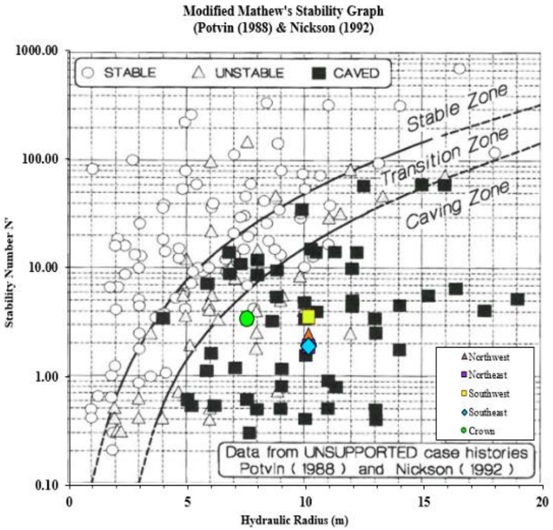
WRS Rock Wall Stability Assessment - Empirical

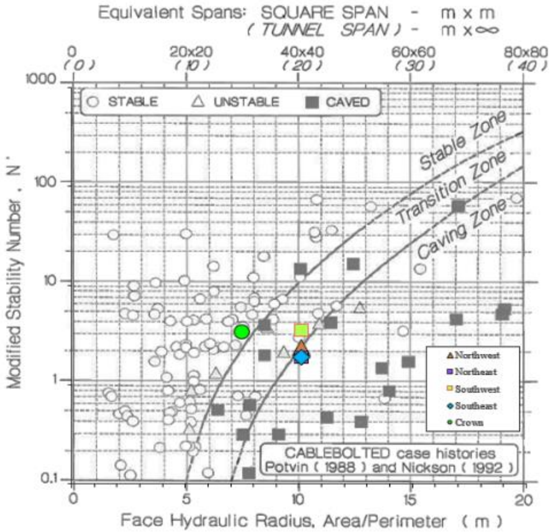
- For completeness, and to aid in communication to mining team, empirical stability assessments of wall and crown stability carried out (Matthews-Potvin)
- Unsupported conditions – all cases unstable (mid range parameters, best case and worst case)
- Supported conditions → manageable crown stability (worst case conditions = transitional)
- Limitations of the empirical method are several (universal applicability, 2-D to a, b and c parameter corrections, estimate for tendon lengths to provide stability → hence kinematic and numerical assessments)

	Dimension						Dolerite - ToM																		
Wall I.D.	Length (N-S), m	Width (E-W), m	Height, m	Area, m²	Perimeter, m	Hydraulic Radius, HR	Q_{med}	Q_{min}	Q_{max}	UCS (MPa)	Sig1 (Map3D)	UCS / Sig1 (Map3D)	Q'_{med}	Q'_{min}	Q'_{max}	a (result)	b (result)	c (result)	N'_{med}	N'_{min}	N'_{max}	Stability-med	Stability-min	Stability-max
SW Side		30	62	1860	184	10.1	4	0.4	10	210	33.0	6.4	4	0.4	10	0.59	0.3	5	3.6	0.4	9.0	Unstable	Unstable	Unstable
NW Side	30		62	1860	184	10.1	4	0.4	10	210	33.0	6.4	4	0.4	10	0.59	0.2	5	2.4	0.2	6.0	Unstable	Unstable	Unstable
NE Side		30	62	1860	184	10.1	4	0.4	10	210	33.0	6.4	4	0.4	10	0.59	0.2	4	1.9	0.2	4.7	Unstable	Unstable	Unstable
SE Side	30		62	1860	184	10.1	4	0.4	10	210	33.0	6.4	4	0.4	10	0.59	0.2	4	1.9	0.2	4.7	Unstable	Unstable	Unstable
Back	30	30		900	120	7.5	4	0.4	10	210	36.0	5.8	4	0.4	10	0.53	0.8	2	3.4	0.3	8.5	Unstable	Unstable	Transition

WRS Rock Wall Stability Assessment - Empirical

- Dolerite, ToM (mid range rock characteristics)

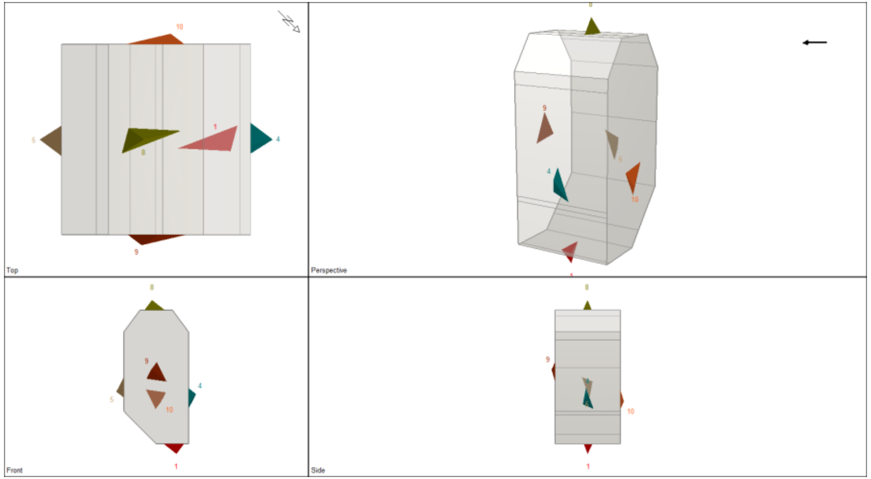


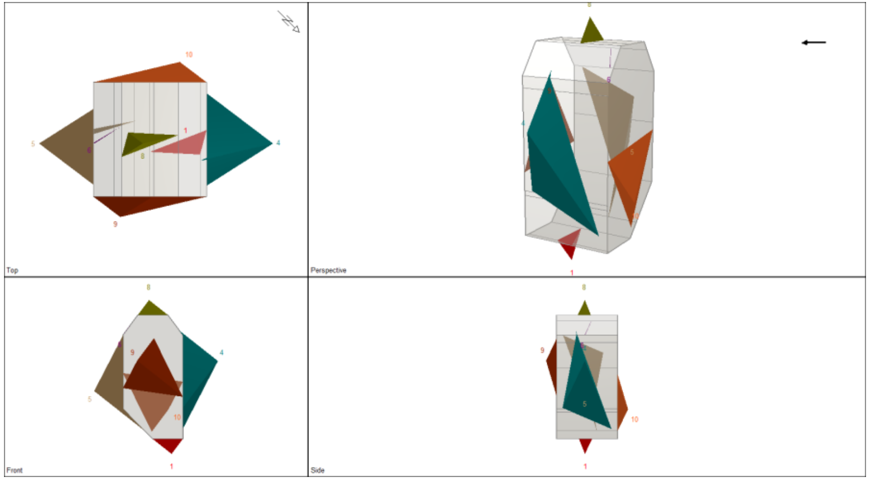


WRS Rock Wall Stability Assessment - Kinematic

- Sidewall and crown (back) stability tests carried out for structural (discontinuity) influence, i.e. wedge failure potential – UnWedge (Rocscience)
- Scenarios tested (10m and 50m joint length (persistence) scenarios in all cases, in the absence of complete variability data to test statistical probability distributions):
  - ❑ ToM Dolerite, Metasediments (dataset A), Metasediments (dataset B)
  - ❑ BoM Marble (61m height, K01)
  - ❑ BoM Marble (77m height, K02; rotated orientation not considered)
- Objective for testing discrete persistence scenarios to estimate relative stability for large and smaller wedges, and therefore expectation for smaller blocks to fail
- Consequence of block failure dependent on utilisation of the stopes
  - ❑ Require nett volume change = 0m^3, i.e. effect of rock wall failure on WRS is offset by commensurate growth in lateral extent (when is failure catastrophic, or intolerable?)
  - ❑ Non-entry stopes, i.e. personnel safety eliminated
  - ❑ Crown stability required to prevent migration upwards, i.e. to prevent the usable stope volume from diminishing, and to facilitate late stage access for backfill

WRS Rock Wall Stability Assessment - Kinematic





WRS Rock Wall Stability Assessment - Kinematic

Persistence (m)	Condition	Parameter	Floor wedge [1]	Roof wedge [8]	SE crown wedge [6]	NW side wedge [4]	SE side wedge [5]	NE side wedge [9]	SW side wedge [10]
10		**Wedge Volume [m3]**	26.0	**26.0**	-	**22.9**	**22.4**	**21.0**	**21.0**
		Wedge Weight [MN]	0.74	0.74	-	0.65	0.64	0.60	0.60
		Wedge Mass (10^3 kg)	75.5	75.5	-	66.7	64.9	61.0	61.0
		Excavation Face Area [m2]	16.9	16.9	-	19.6	19.3	38.3	38.3
		Approximate wedge width [m]	4.1	**4.1**		**4.4**	**4.4**	**6.2**	**6.2**
		Apex Height [m]	4.6	**4.6**	-	**3.5**	**3.5**	**1.7**	**1.7**
		Aspect Ratio (Apex height / sqrt (face area))	1.1	1.1	-	0.8	0.8	0.3	0.3
		Apex Angle [degrees]	36.9	36.9	-	36.9	36.9	36.9	38.1
	Wet	**Factor of Safety**	stable	**0.0**	-	**0.2**	1.1	**0.1**	**0.4**
	Dry		stable	**0.9**	-	1.4	4.1	1.3	2.4
50		**Wedge Volume [m3]**	105.4	**105.4**	**0.0**	**2818.4**	**1552.1**	**710.9**	**711.3**
		Wedge Weight [MN]	3.01	3.01	0.00	80.32	44.24	20.26	20.27
		Wedge Mass (10^3 kg)	306.3	306.3	0.1	8187.9	4509.2	2065.3	2066.6
		Excavation Face Area [m2]	42.9	42.9	1.9	485.7	334.4	400.6	400.7
		Approximate wedge width [m]	6.5	**6.5**		**22.0**	**18.3**	**20.0**	**20.0**
		Apex Height [m]	7.4	**7.4**	**0.1**	**17.4**	**14.3**	**5.3**	**5.3**
		Aspect Ratio (Apex height / sqrt (face area))	1.1	1.1	-	0.8	0.8	0.3	0.3
		Apex Angle [degrees]	36.9	36.9	38.1	36.9	36.9	36.9	38.1
	Wet	**Factor of Safety**	stable	**0.0**	-	**0.2**	1.1	**0.1**	**0.4**
	Dry		stable	**0.6**	26.9	**0.6**	3.1	**0.6**	1.5
	Influential joint set (input into Potvin stability analysis)	Failure Mode	unconditionally stable wedge	falling wedge	-	wedge sliding on joint 1	wedge sliding along line of intersection of joints 3 and 4	wedge sliding on joint 3	wedge sliding along line of intersection of joints 1 and 4
		Dip (°)	-	59	-	59	70	70	80
		Dip Direction (°)	-	150	-	150	228	228	024
		Angle between joint and free surface	-	59	-	31	20	20	10
		b value	-	0.8	-	0.2	0.2	0.2	0.3
		c value	-	2.0	-	5.0	4.0	4.0	5.0
		Side-wall most at risk (Potvin)	-	-	-	-	**SE side**	**NE side**	-
		Side-wall most at risk (Unwedge)	-	-	-	**NW side**	-	**NE side**	-
		Affected middling	-	-	-	60m middling	60m middling	45m middling	45m middling
		Resulting middling	-	-	-	42.6 m		34.4m	

Outcomes

- WRS proposal acceptable in concept
- Crown stability will be required with the installation of long anchors (>10m)
- Side wall failure expected to be effectively certain : extent and potential catastrophic impact of failure to be firmed
- Dimensions and spacings provisionally acceptable, with cognizance of potential residual risk for which improved quantification required by means of:
  - ❑ Improved characterisation data : drilling, mapping
  - ❑ Improved numerical analysis (FE or DE modelling to incorporate structure and stress interactions)
  - ❑ Improved probabilistic distribution analysis for wedge size distribution and potential for silting up bottom egress
  - ❑ Improved estimate of extent of fracture propagation affecting top access for late stage access to backfill
  - ❑ Firm up on ground support requirements for crown stability
  - ❑ Timing for additional assessment, Q2 2024 (ToM stopes top access under development)

END