Rock Engineering for an Underground Storage Facility in Singapore

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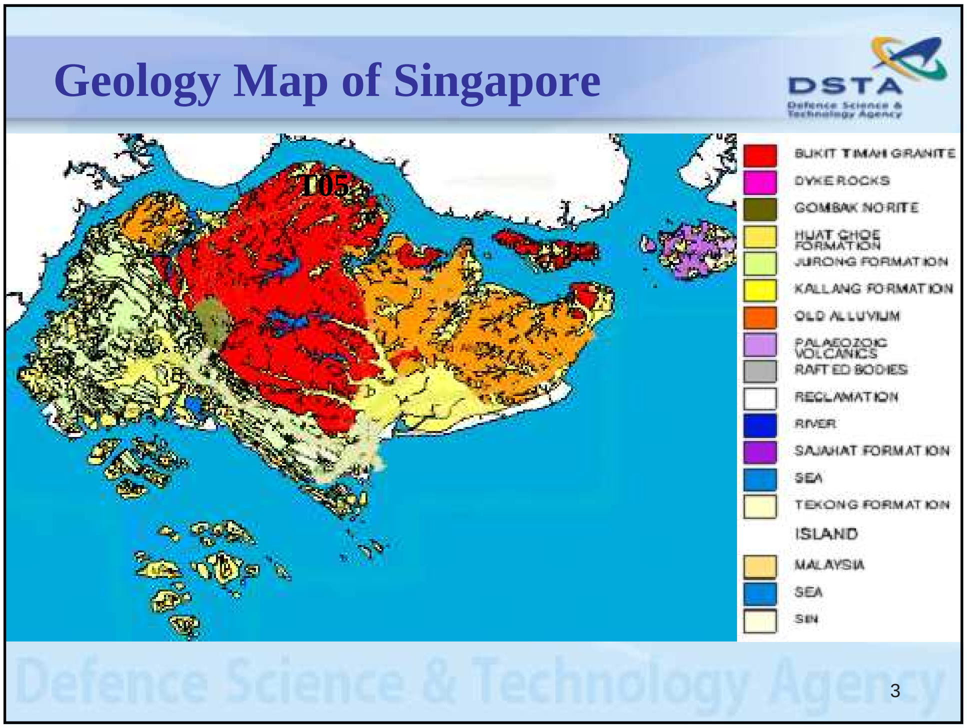
Outline

- Brief project introduction
- Site characterisation and rock mass classification
- Tunnel design and construction
- Instrumentation and monitoring
- Conclusions

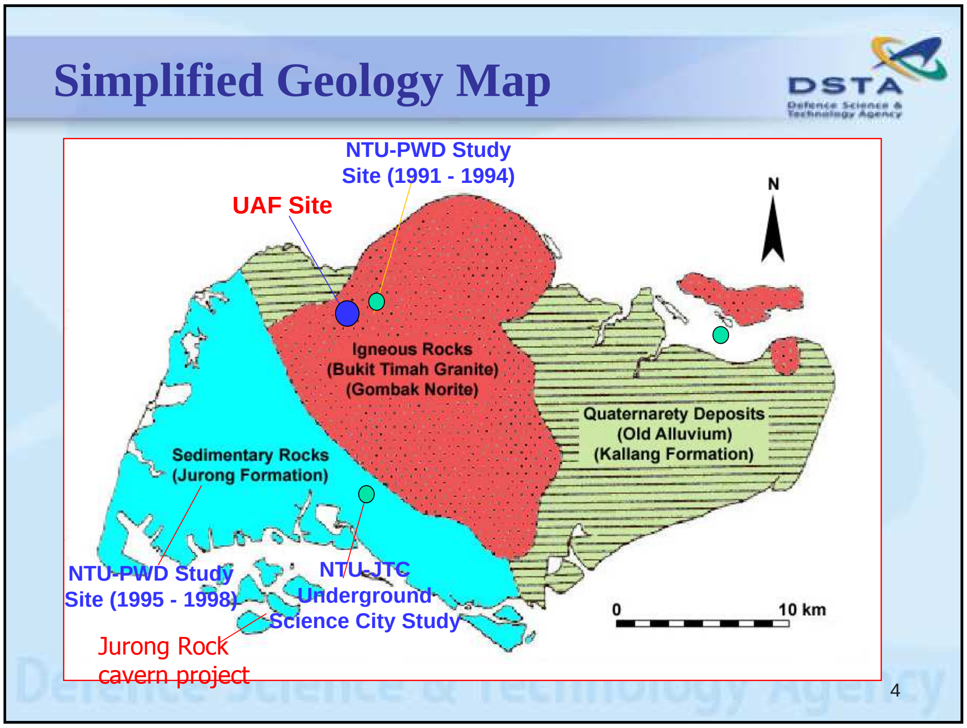


Geology Map of Singapore

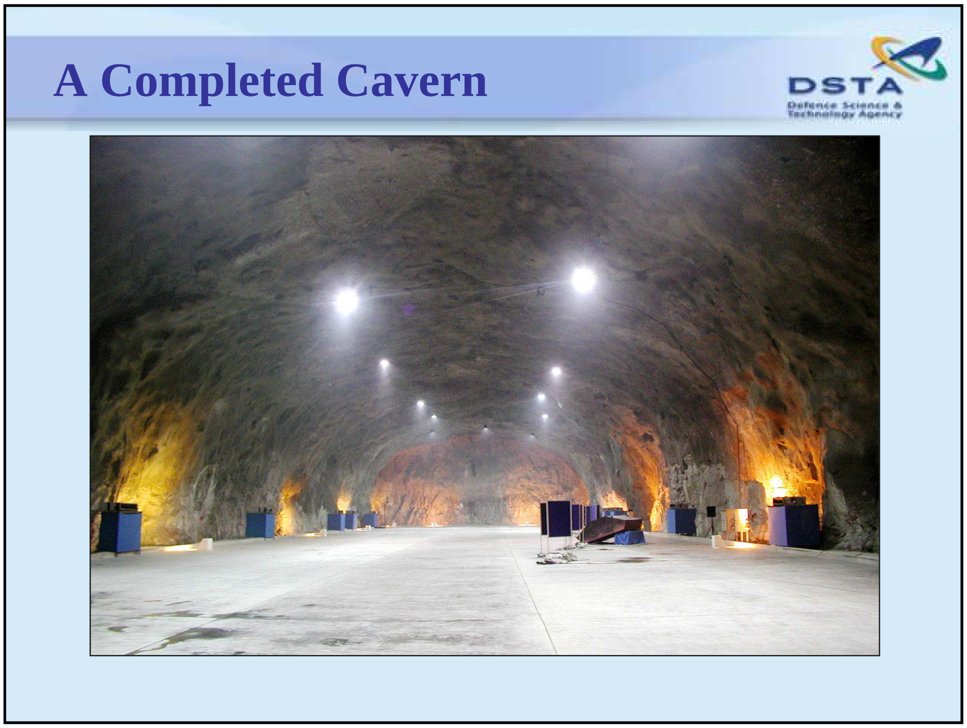
- 🟥 BUKIT TIMAH GRANITE
- 🟪 DYKE ROCKS
- 🟫 GOMBAK NORITE
- 🟨 HUAT CHOE FORMATION
- 🟩 JURONG FORMATION
- 🟨 KALLANG FORMATION
- 🟧 OLD ALLUVIUM
- 🟪 PALAEOZOIC VOLCANICS
- ⬜ RAFTED BODIES
- ⬜ RECLAMATION
- 🟦 RIVER
- 🟪 SAJAHAT FORMATION
- 🟦 SEA
- ⬜ TEKONG FORMATION

ISLAND

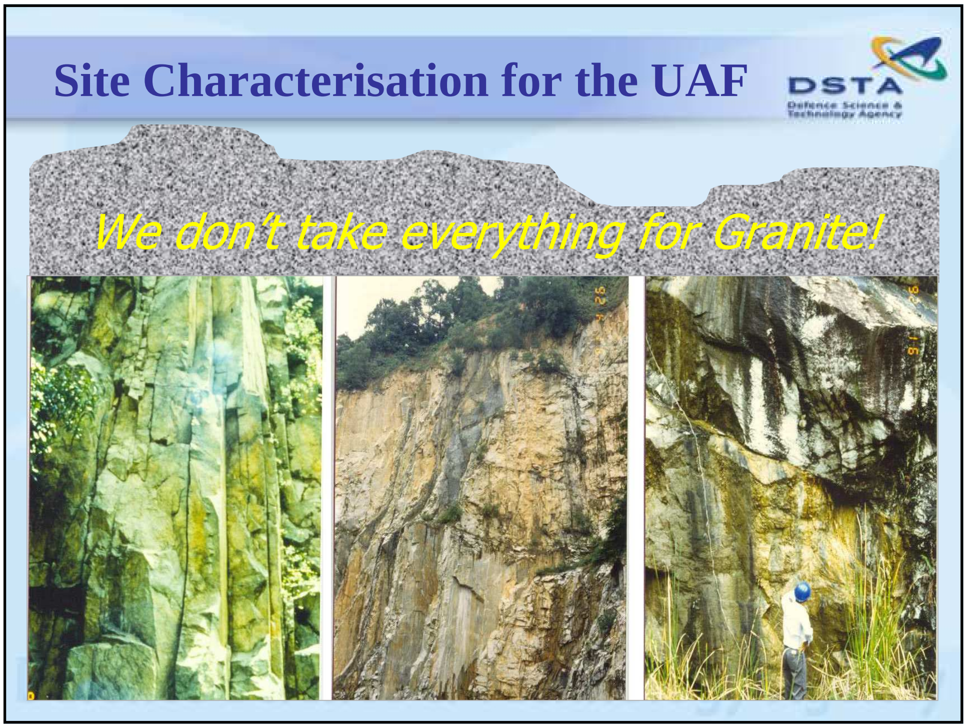
- 🟧 MALAYSIA
- 🟦 SEA
- ⬜ SIN



Simplified Geology Map

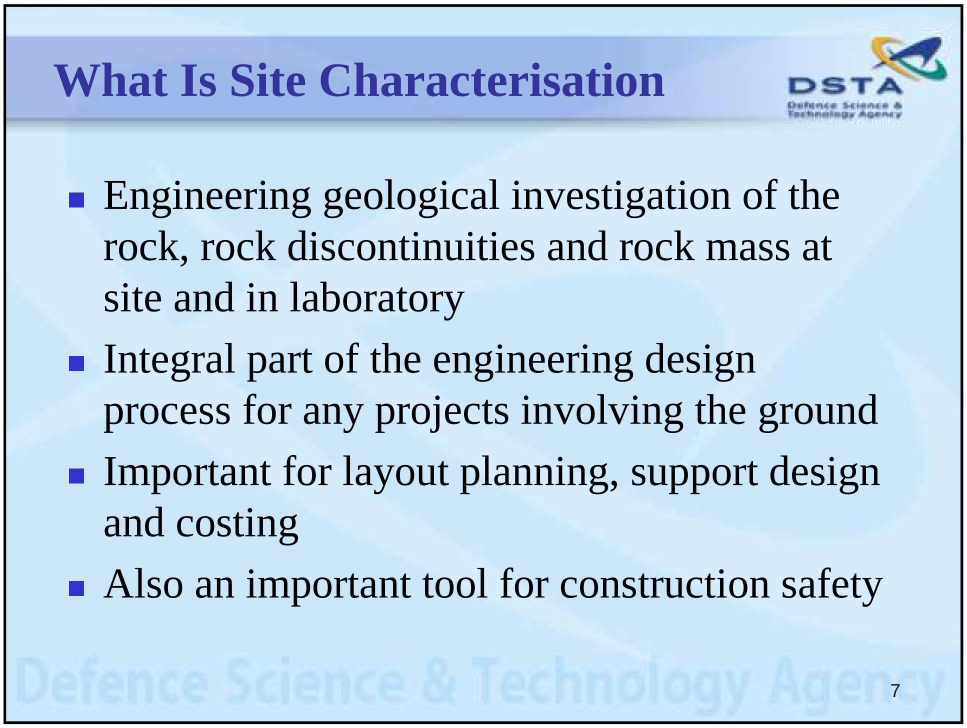


A Completed Cavern



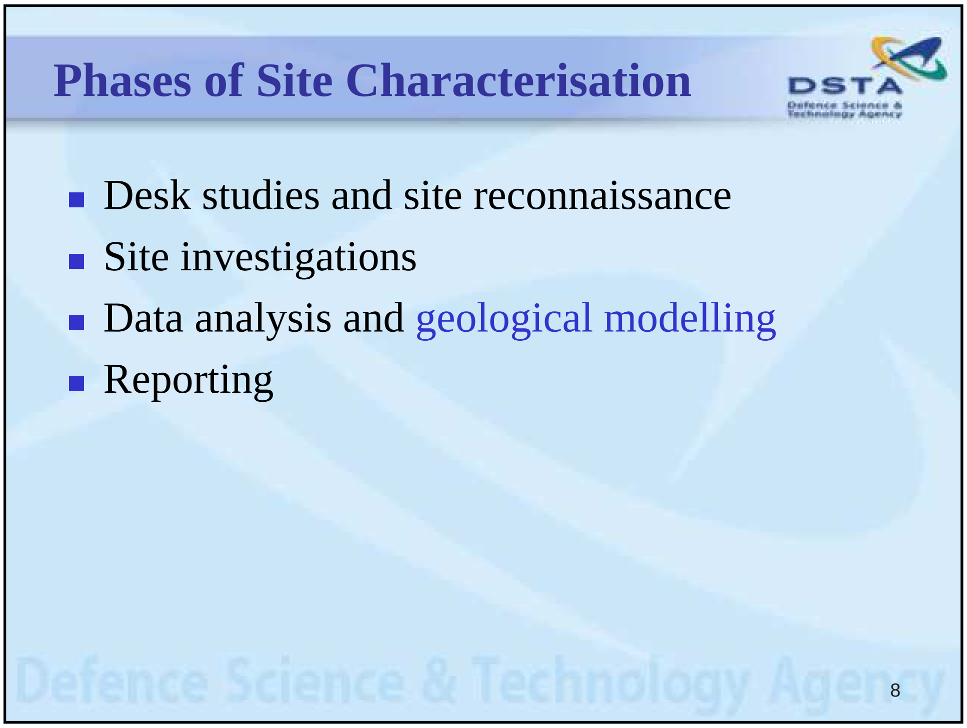
Site Characterisation for the UAF

We don't take everything for Granite!



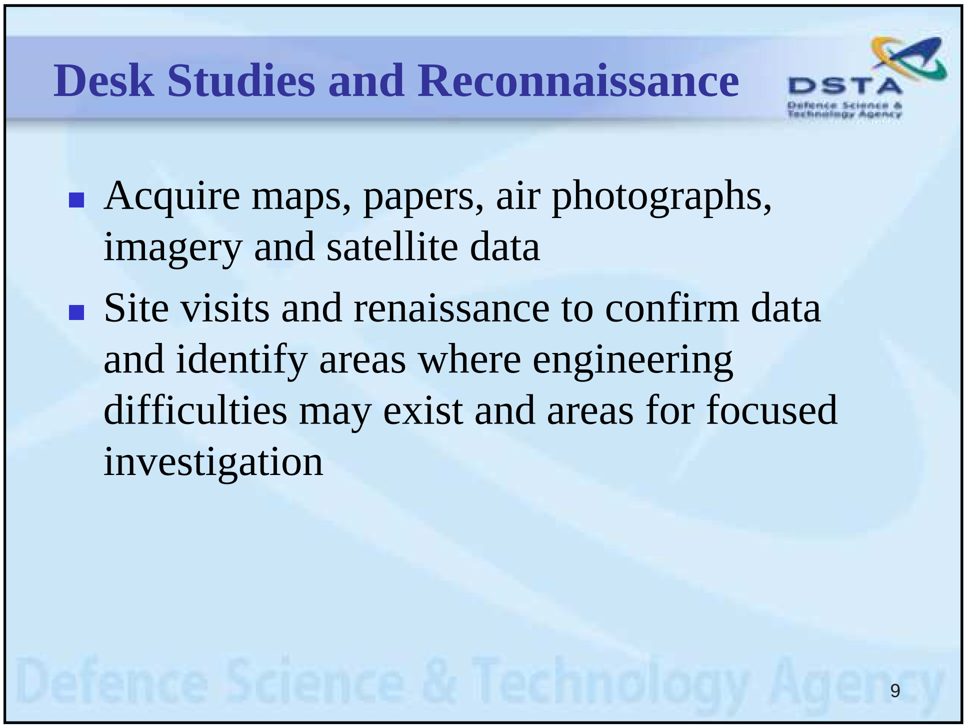
What Is Site Characterisation

- Engineering geological investigation of the rock, rock discontinuities and rock mass at site and in laboratory
- Integral part of the engineering design process for any projects involving the ground
- Important for layout planning, support design and costing
- Also an important tool for construction safety



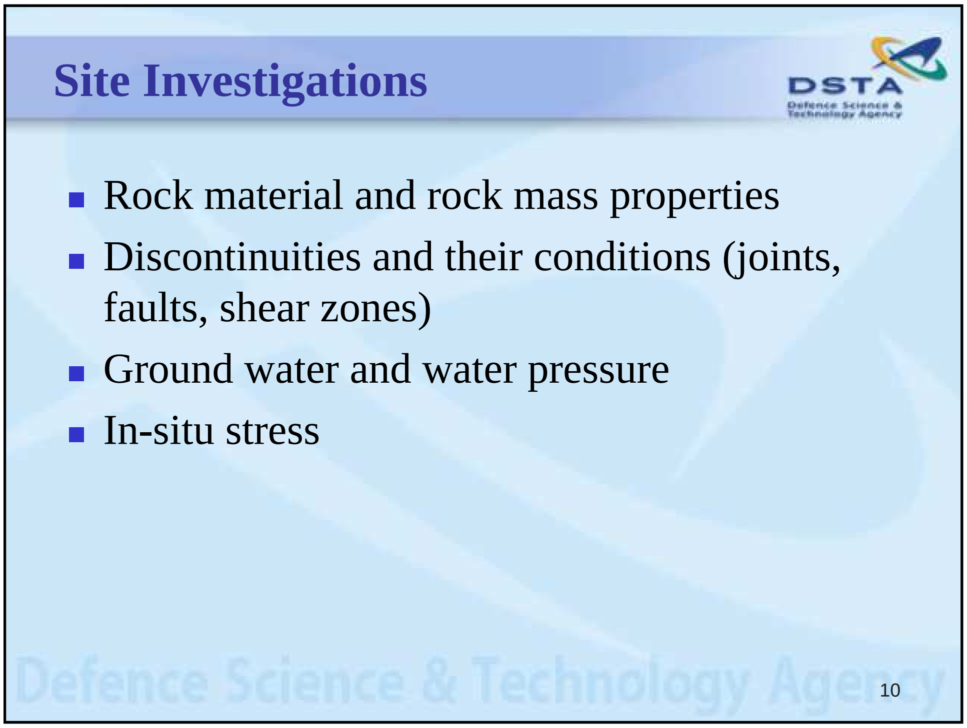
Phases of Site Characterisation

- Desk studies and site reconnaissance
- Site investigations
- Data analysis and geological modelling
- Reporting



Desk Studies and Reconnaissance

- Acquire maps, papers, air photographs, imagery and satellite data
- Site visits and renaissance to confirm data and identify areas where engineering difficulties may exist and areas for focused investigation



Site Investigations

- Rock material and rock mass properties
- Discontinuities and their conditions (joints, faults, shear zones)
- Ground water and water pressure
- In-situ stress

Techniques for Site Investigation

- Geological mapping (exposure and discontinuities)
- Geophysical surveys (detective work)
- Exploratory drilling (soil drilling and diamond core drilling)
- In-situ testing (rock mass properties)
- Laboratory testing (rock material properties)

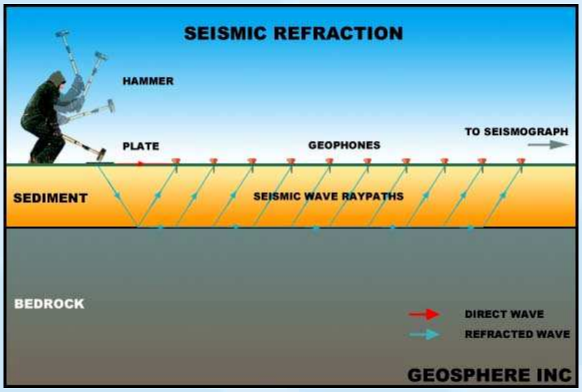
Geophysical Surveys

- Seismic refraction and reflection
- Electrical resistivity
- Coupled seismic reflection (good vertical resolution) and electrical resistivity (good horizontal resolution) strong recommended
- Obtains data on overburden thickness, bedrock elevation, seismic velocities of geological layers, and major geological structures

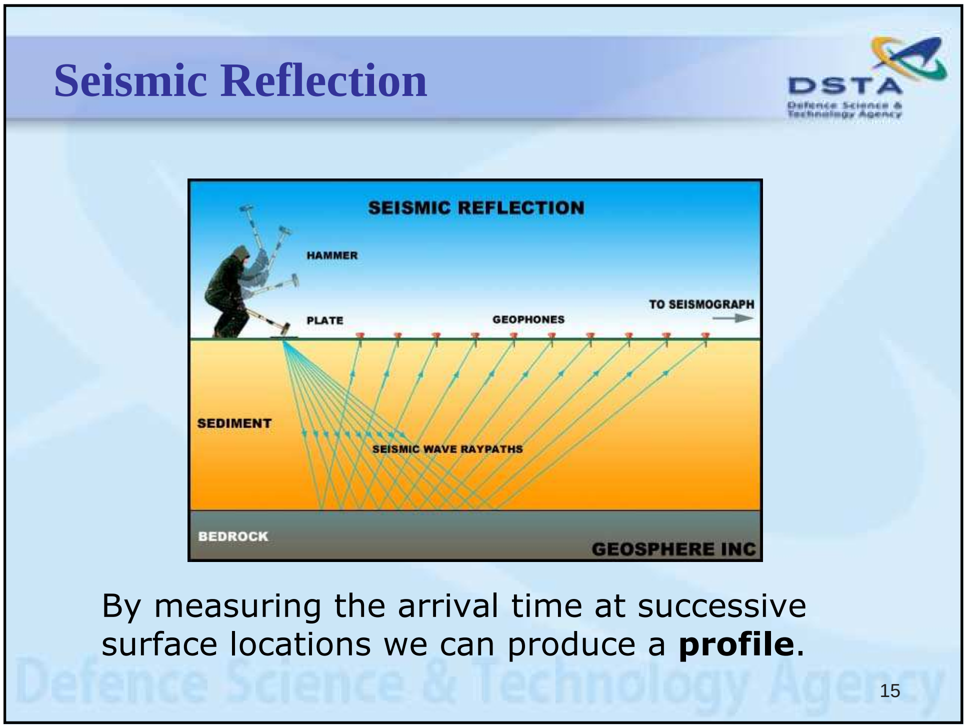
Methods of Investigation for UAF

Type	Methods	Objective
Drilling	Soil boring; diamond core drilling	Overburden, and rock cores
Surface geophysical surveys	Seismic refraction/reflection; electric resistivity tomography	Main geological structures; overburden depth
Borehole surveys and testing	Borehole logging; seismic logging; borehole camera acoustic imaging; impression packer; borehole radar; Lugeon tests; rising head/falling head tests; cross-hole tomography	Ground temperature; Seismic velocities; joints; and permeability; geological structures
Laboratory tests	Point load; uniaxial/triaxial compression; Brazil tensile; 3-point flexural	Mechanical properties of intact rock and rock joints
In situ stress	Hydraulic fracturing; 3-D overcoring	Hydraulic fracturing; 3-D overcoring (during construction)

Seismic Refraction

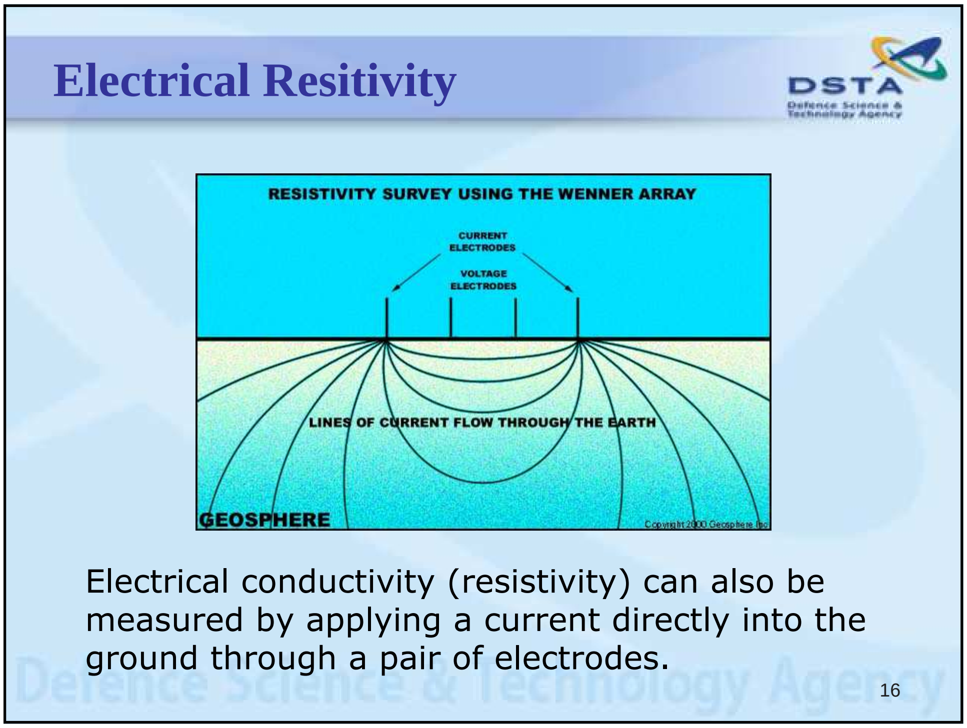


When a sound wave crosses an interface between layers of two different velocities, the wave is **refracted**.



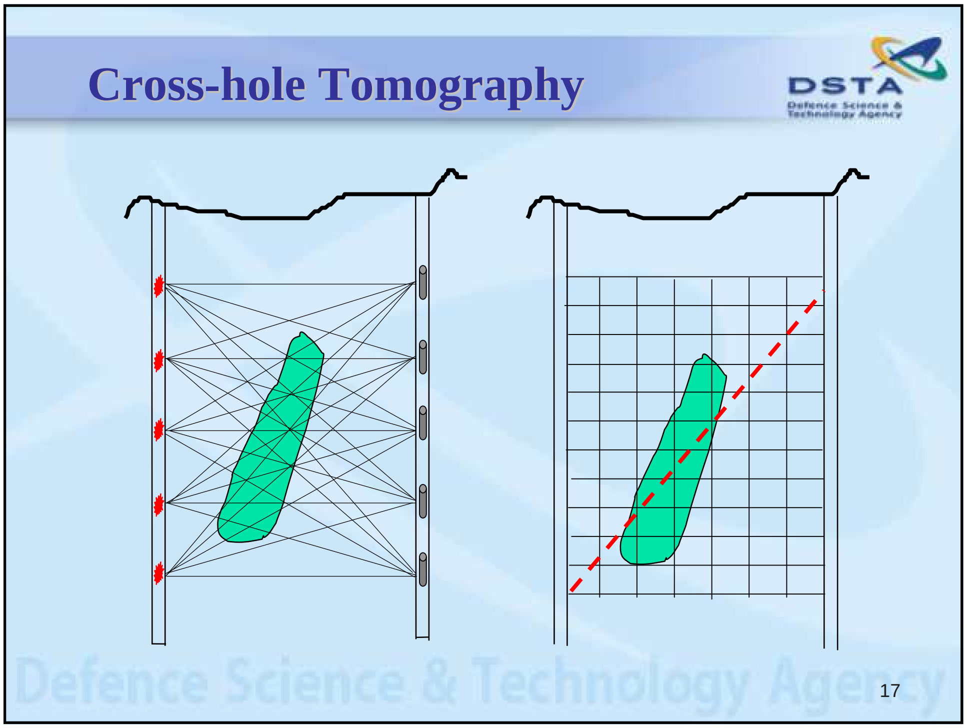
Seismic Reflection

By measuring the arrival time at successive surface locations we can produce a **profile**.

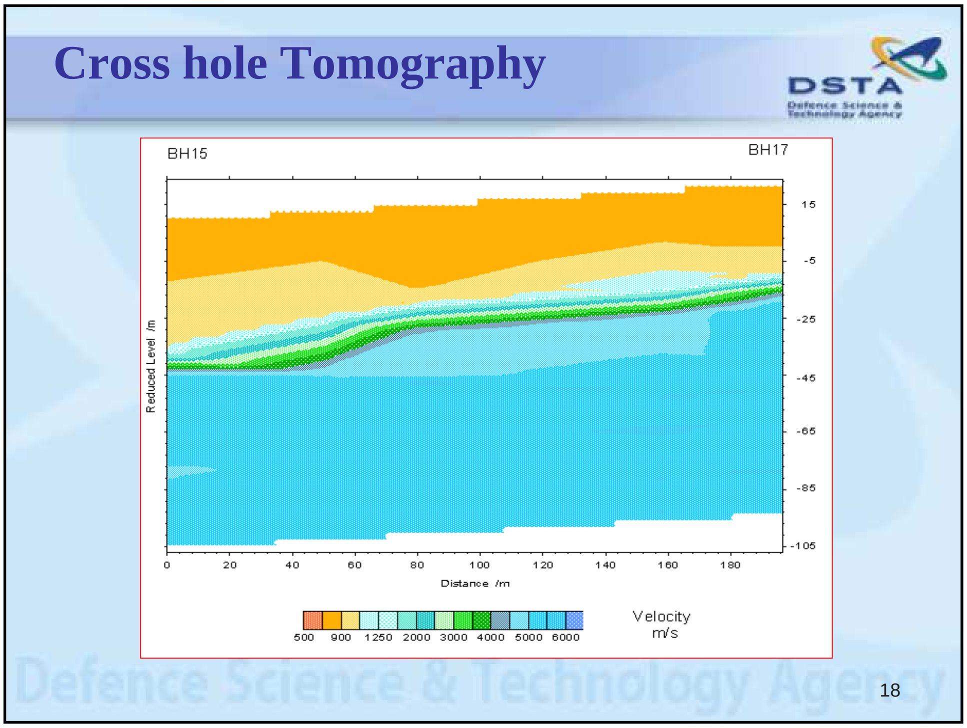


Electrical Resitivity

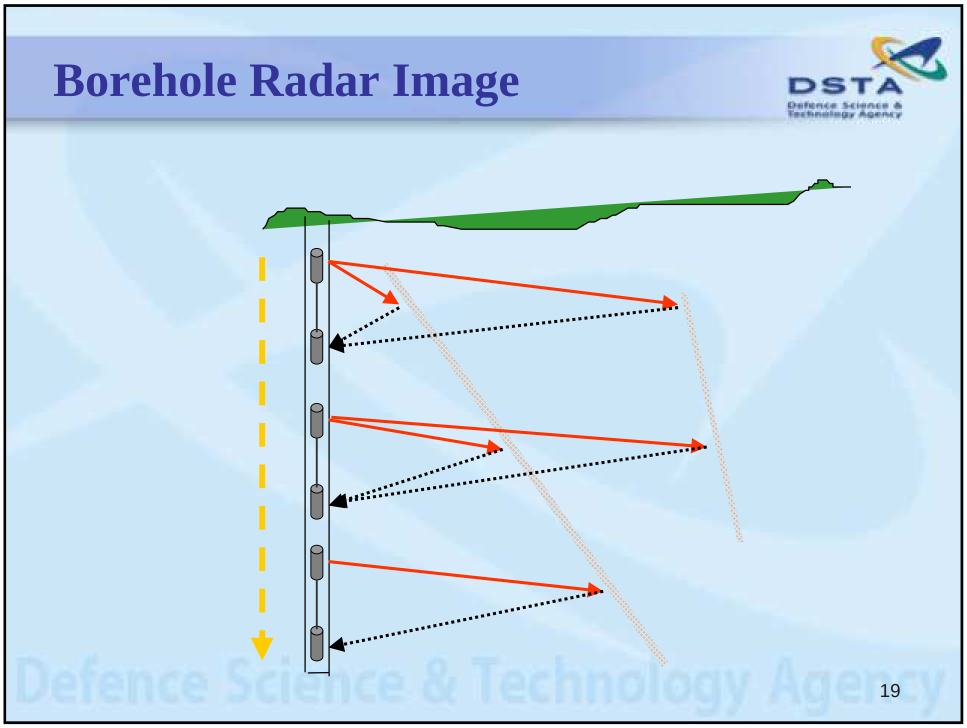
Electrical conductivity (resistivity) can also be measured by applying a current directly into the ground through a pair of electrodes.



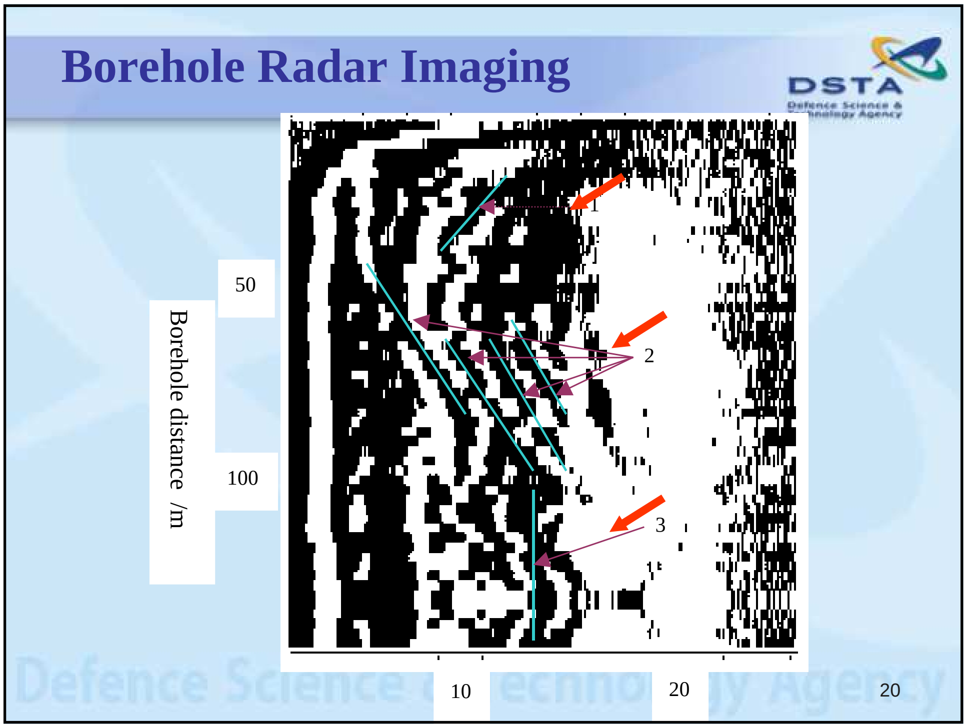
Cross-hole Tomography



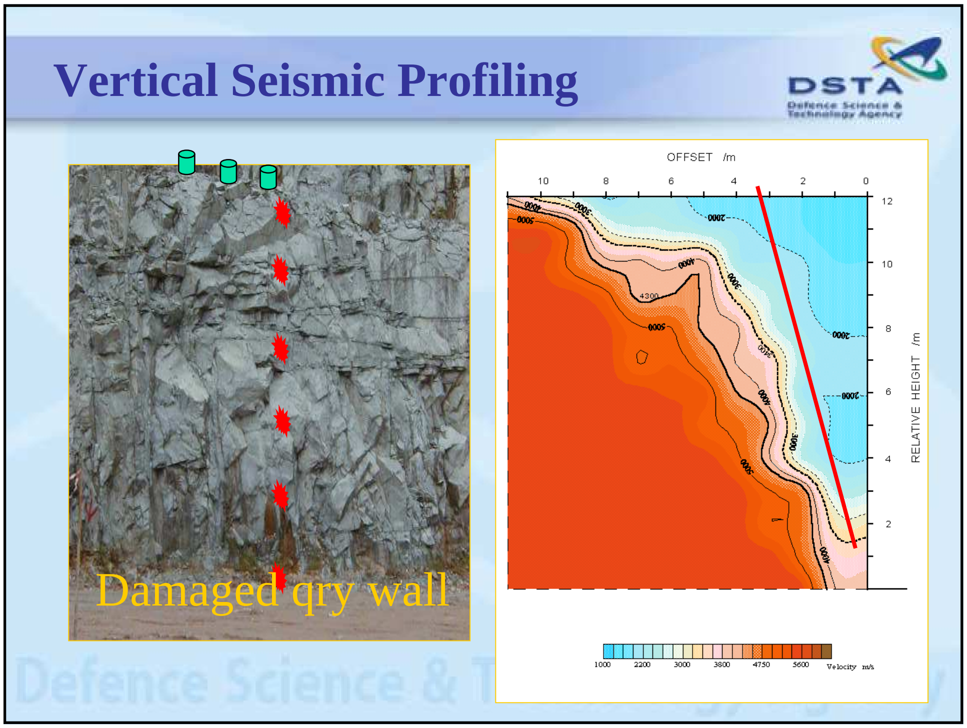
Cross hole Tomography



Borehole Radar Image

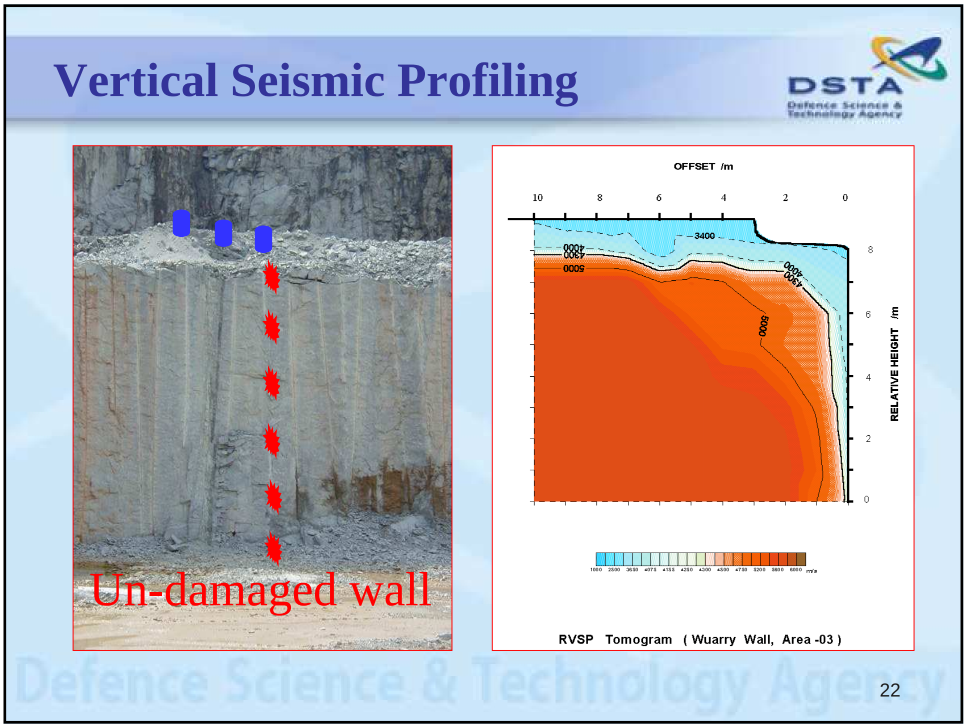


Borehole Radar Imaging



Vertical Seismic Profiling

Damaged qry wall

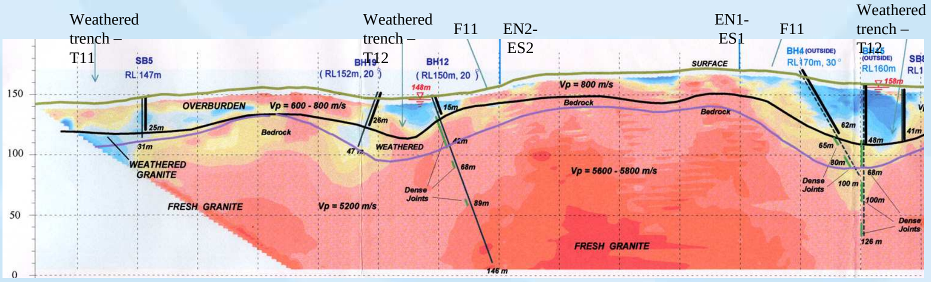


Vertical Seismic Profiling

Un-damaged wall

RVSP Tomogram (Wuarry Wall, Area -03)

Composite Geological Profile



Core Drilling - Fresh Granite

Intact Rock Properties

Properties	Range	Average
Density (g/cm^3)	2.62 ~ 2.67	2.65
Uniaxial compressive strength (MPa)	108.09 ~ 224.89	163.83
Young's modulus (GPa)	37.10 ~ 111.25	65.87
Poisson's ratio	0.14 ~ 0.35	0.24
Cohesion (MPa)	—	24.51
Internal friction angle (^{o})	—	59.02
Point load index	5.6 ~ 16.1	8.7
Brazil tensile strength (MPa)	8.46 ~ 14.30	11.71
Three-point tensile strength (MPa)	13.25 ~ 27.30	19.94

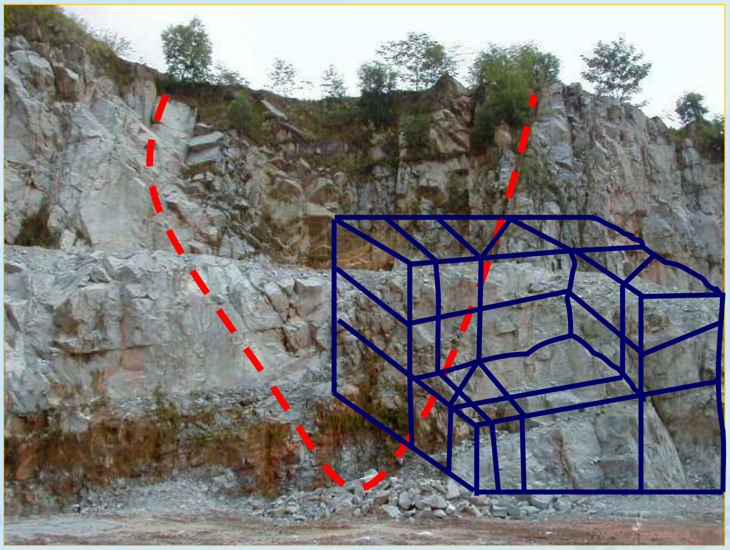
Core Drilling - Weathered Granite

LE(S)0371C.02 SITE CHARACTERISATION FOR A SITE AT MANDAI
BH 15
BOX 3

C.R. NO.	DEPTH (M)	TCR/	SCR/	RQD/
11	60.00-61.00	70	20	20
12	61.00-62.00	94	72	56
13	62.00-63.00	98	0	0
14	63.00-64.50	100	10	10

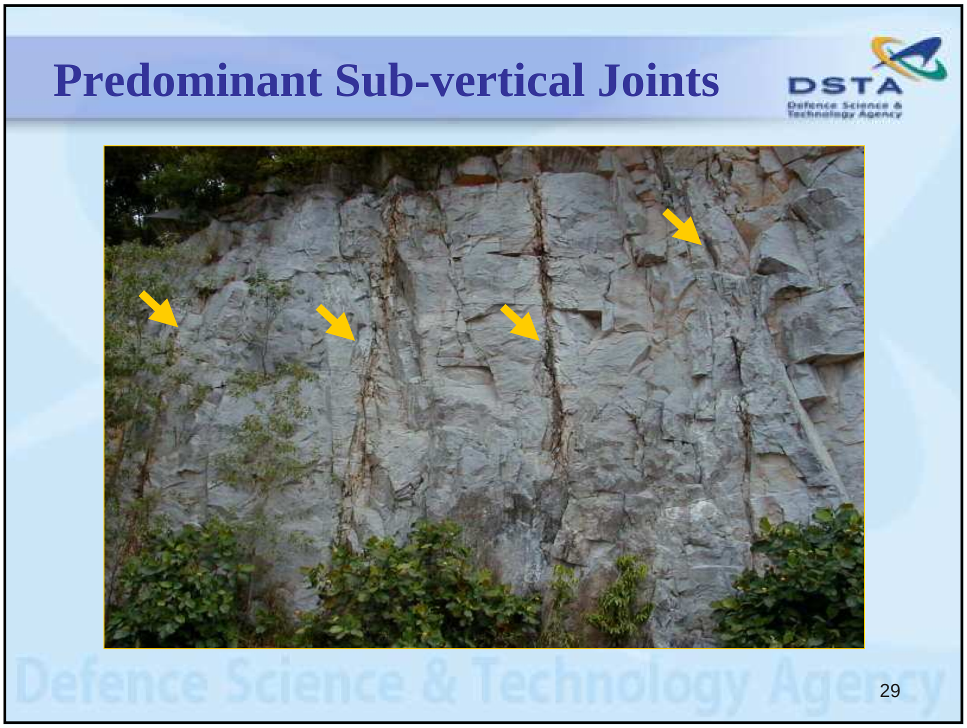
15/2/1999

Outcrop of a Weathered Trench

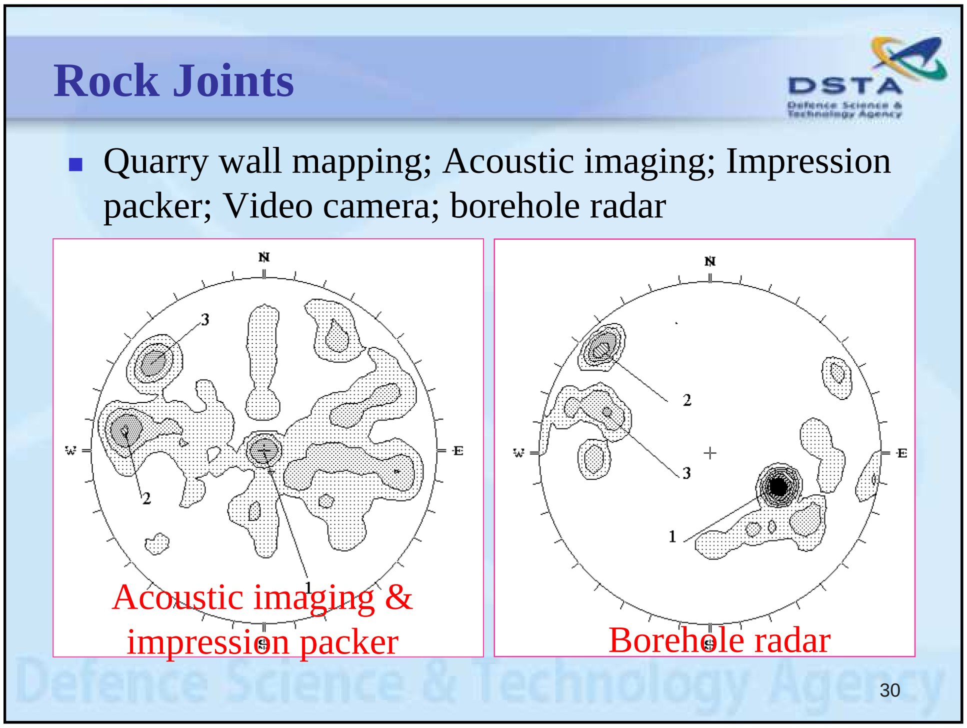


Weathered Trenches

Trench	Strike	Extent, m	Depth, m	Weathering Grade
T1	SN to NE30o	750	39	II, III
T2	NNW to NE30	950	80	II, III, IV
T3	NE25	900	47	II, III



Predominant Sub-vertical Joints

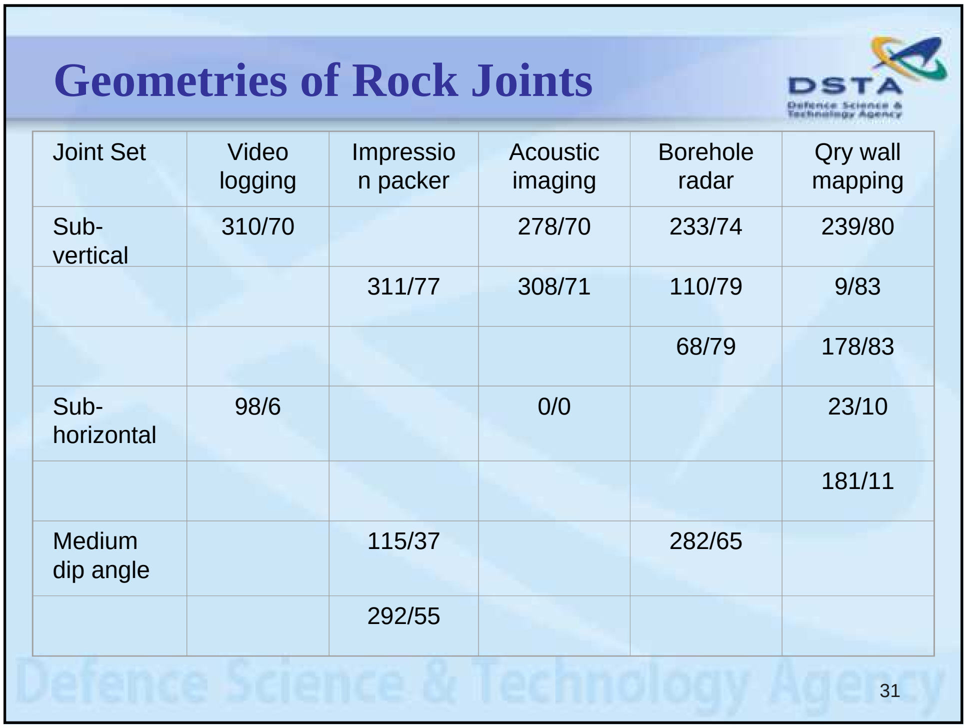


Rock Joints

- Quarry wall mapping; Acoustic imaging; Impression packer; Video camera; borehole radar

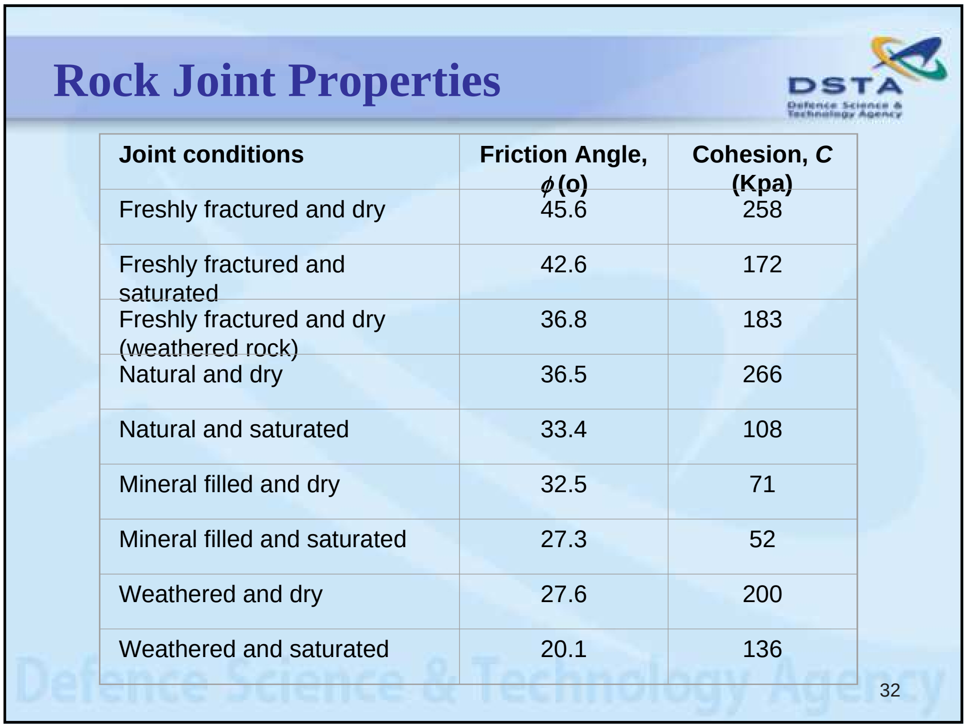
Acoustic imaging & impression packer

Borehole radar



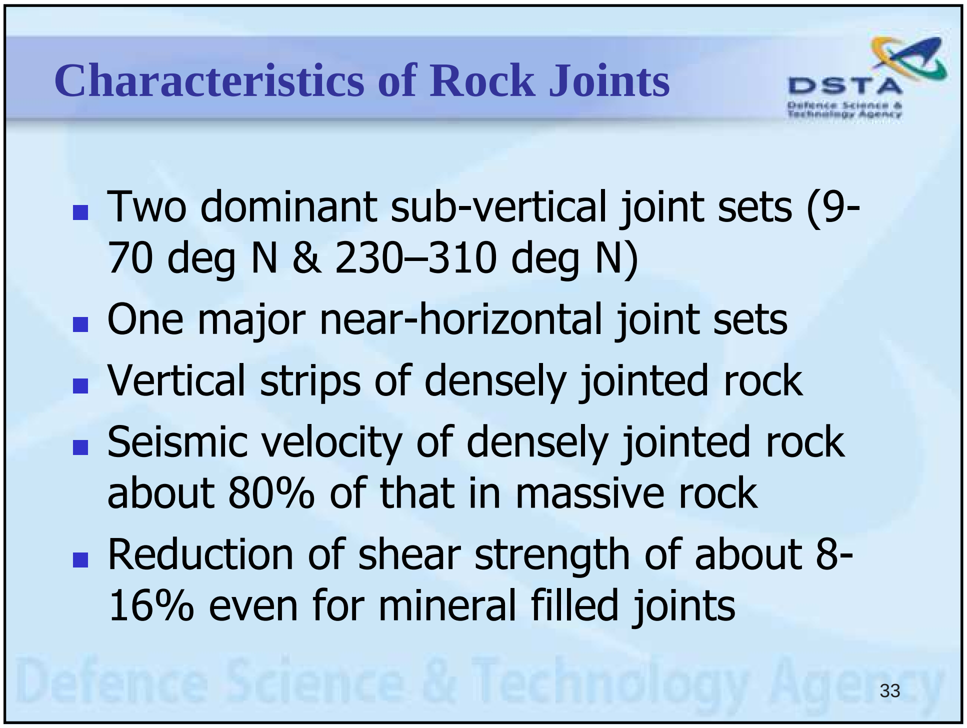
Geometries of Rock Joints

Joint Set	Video logging	Impression packer	Acoustic imaging	Borehole radar	Qry wall mapping
Sub-vertical	310/70		278/70	233/74	239/80
		311/77	308/71	110/79	9/83
				68/79	178/83
Sub-horizontal	98/6		0/0		23/10
					181/11
Medium dip angle		115/37		282/65	
		292/55			



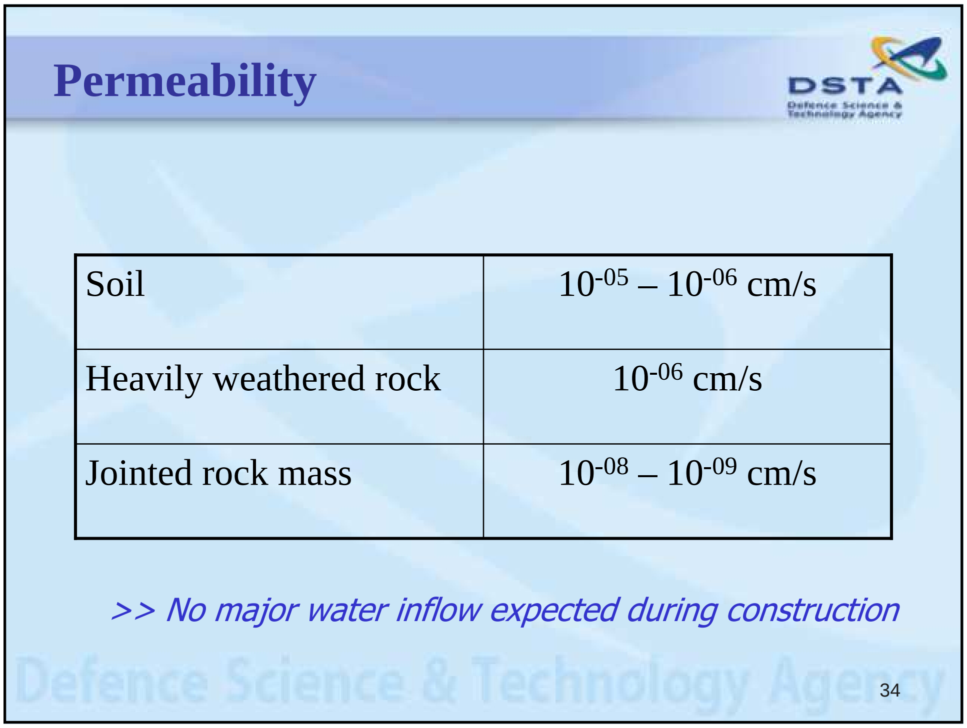
Rock Joint Properties

Joint conditions	**Friction Angle, ϕ (o)**	**Cohesion, *C* (Kpa)**
Freshly fractured and dry	45.6	258
Freshly fractured and saturated	42.6	172
Freshly fractured and dry (weathered rock)	36.8	183
Natural and dry	36.5	266
Natural and saturated	33.4	108
Mineral filled and dry	32.5	71
Mineral filled and saturated	27.3	52
Weathered and dry	27.6	200
Weathered and saturated	20.1	136



Characteristics of Rock Joints

- Two dominant sub-vertical joint sets (9-70 deg N & 230–310 deg N)
- One major near-horizontal joint sets
- Vertical strips of densely jointed rock
- Seismic velocity of densely jointed rock about 80% of that in massive rock
- Reduction of shear strength of about 8-16% even for mineral filled joints



Permeability

Soil	$10^{-05} – 10^{-06}$ cm/s
Heavily weathered rock	10^{-06} cm/s
Jointed rock mass	$10^{-08} – 10^{-09}$ cm/s

>> No major water inflow expected during construction

In situ Stress

- Stresses before excavation (virgin stress)
- Vertical stress $\sigma_v = \gamma H$
- Horizontal stress $\sigma_h = K\,\sigma_v$
- Strong influence of local variations
- Estimate of average horizontal stress factor:

K = 3 - H/500 (for depth < 1000 m)

K = 9/8 - H/800 (for depth > 1000 m)

In Situ Stress

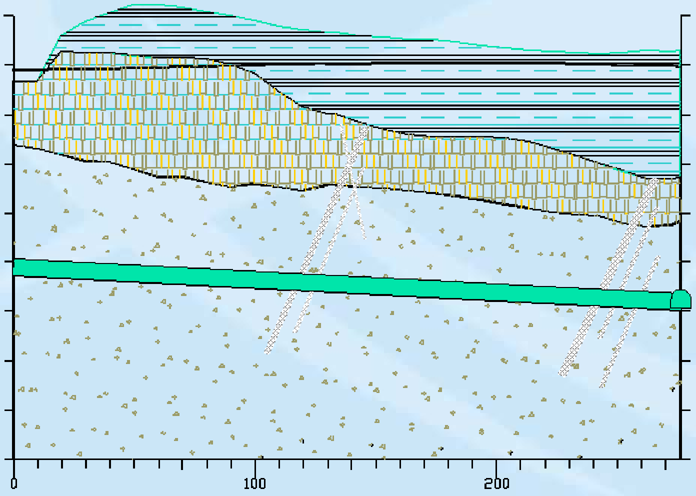
Test Method	**Hydraulic Fracturing**		**3-D Overcoring**	
	Stress, Mpa	Orientation	Stress, Mpa	Orientation
Vertical stress	2.25	---	3.0	---
Maximum horizontal stress	7.3	13^{o}	8.2	67^{o}
Minimum horizontal stress	4.56	103^{o}	3.4	157^{o}

Horizontal stress ratio: $\sigma_v : \sigma_{hmin} : \sigma_{hmax} = 1:2:3$

Summary of Geological Properties

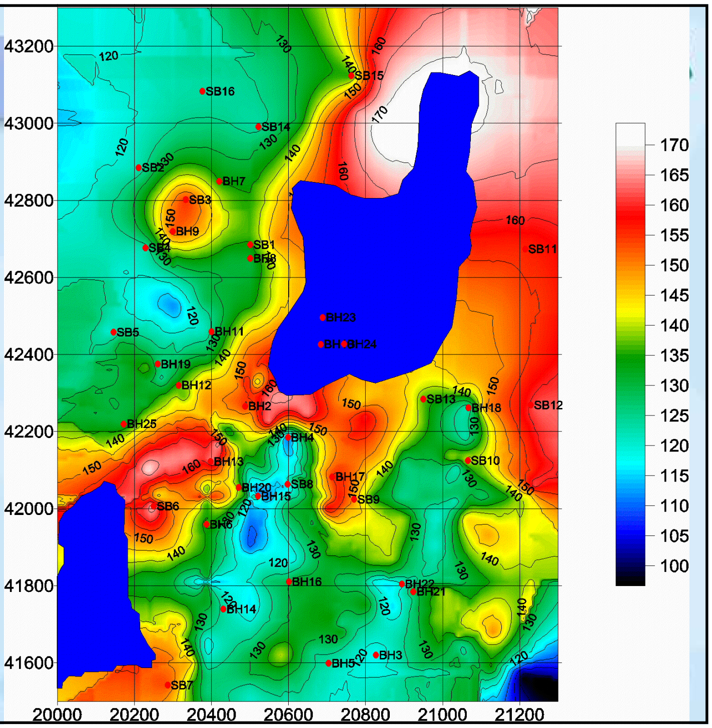
- No major tectonic faults
- Three-layer geological profile
- Deep weathering trenches
- Sub-vertical strips of densely jointed rock
- Favourable high horizontal stresses
- Relatively low permeability
- Rock mass generally good to very good for cavern construction

Geological Model



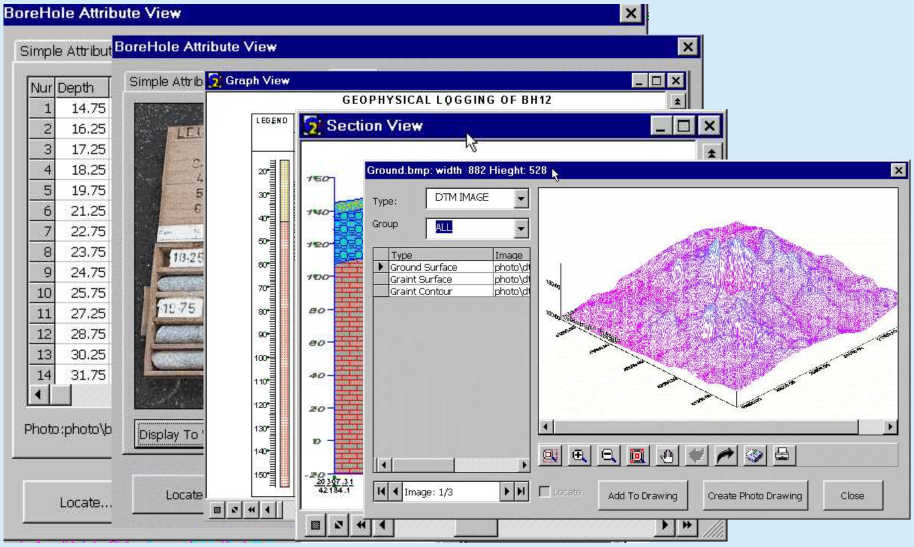
- Three layer formation
  - Residual Soil
  - Weathered granite
  - Fresh granite
- Weathering trenches & dense joint strips

Bed Rock



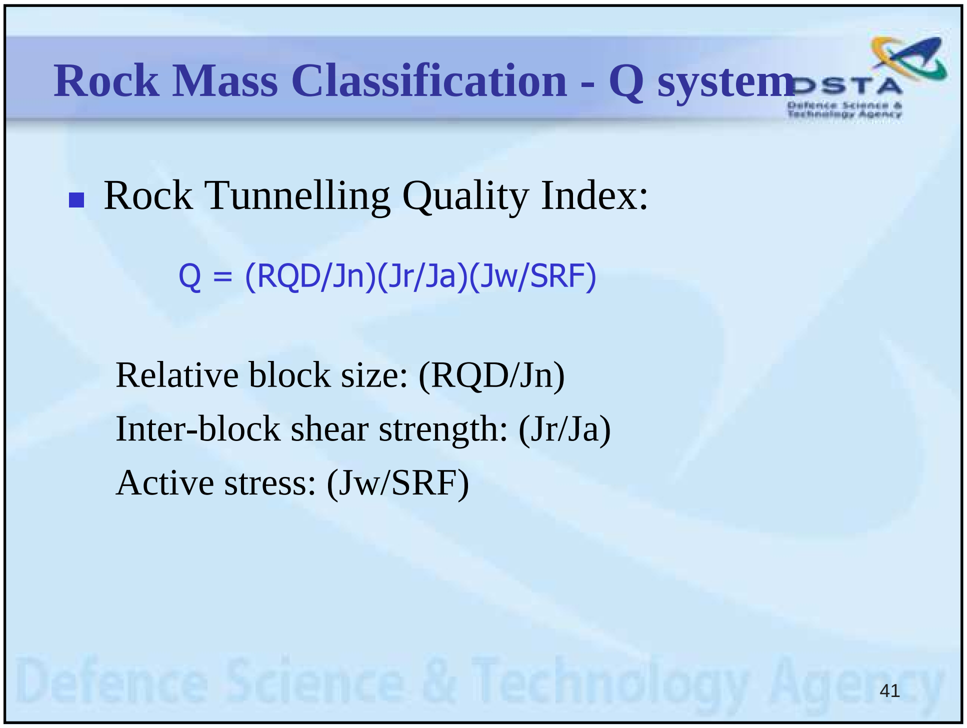
GIS - Geological Database

DSTA
Defence Science & Technology Agency



Type	Image
Ground Surface	photo\d
Graint Surface	photo\d
Graint Contour	photo\d

Nur	Depth
1	14.75
2	16.25
3	17.25
4	18.25
5	19.75
6	21.25
7	22.75
8	23.75
9	24.75
10	25.75
11	27.25
12	28.75
13	30.25
14	31.75

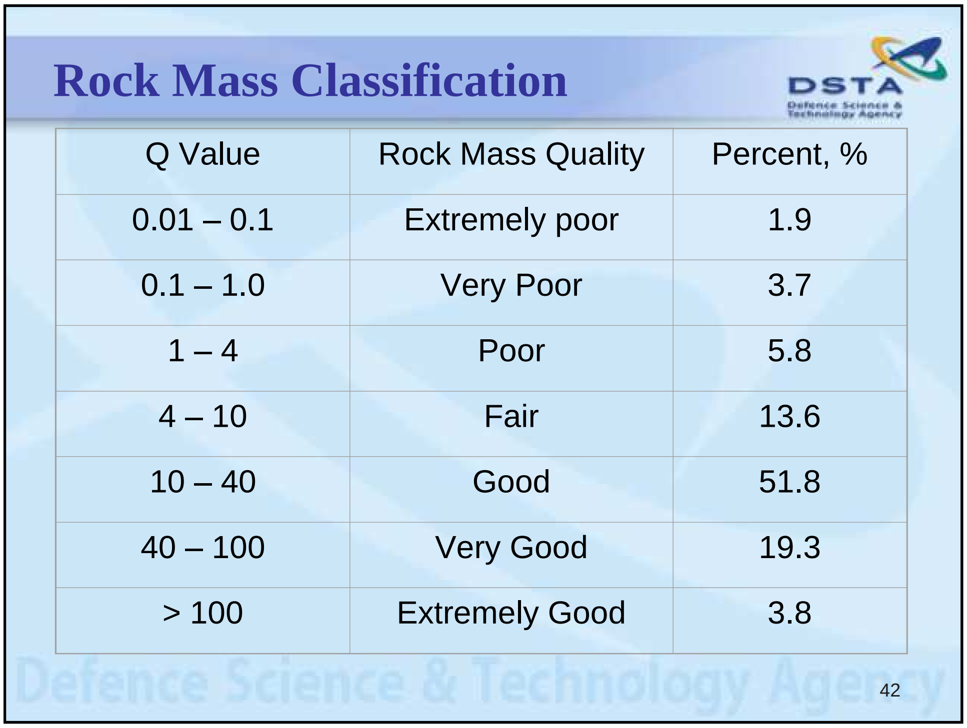


Rock Mass Classification - Q system

- Rock Tunnelling Quality Index:

$$Q = (RQD/Jn)(Jr/Ja)(Jw/SRF)$$

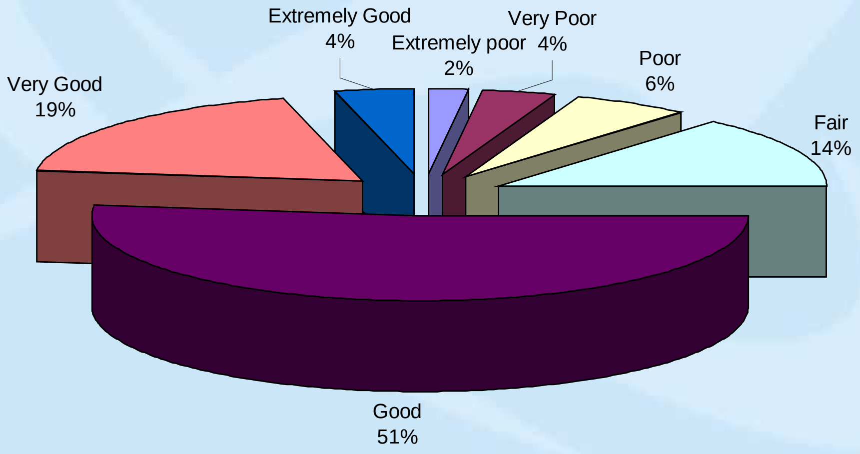
Relative block size: (RQD/Jn)
Inter-block shear strength: (Jr/Ja)
Active stress: (Jw/SRF)



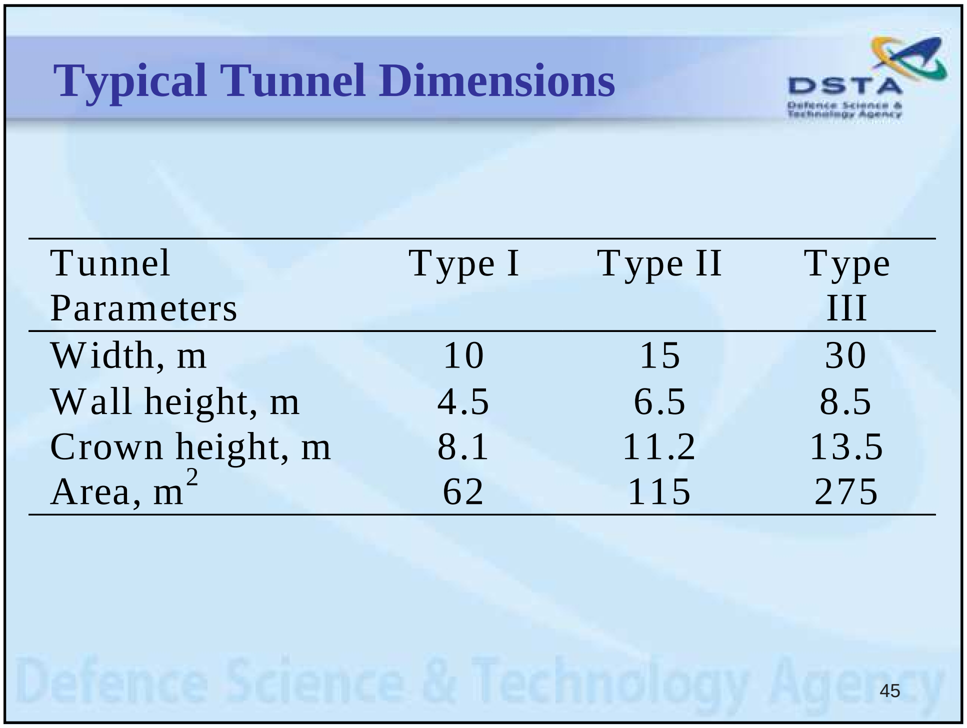
Rock Mass Classification

Q Value	Rock Mass Quality	Percent, %
0.01 – 0.1	Extremely poor	1.9
0.1 – 1.0	Very Poor	3.7
1 – 4	Poor	5.8
4 – 10	Fair	13.6
10 – 40	Good	51.8
40 – 100	Very Good	19.3
> 100	Extremely Good	3.8

Rock Mass Classification

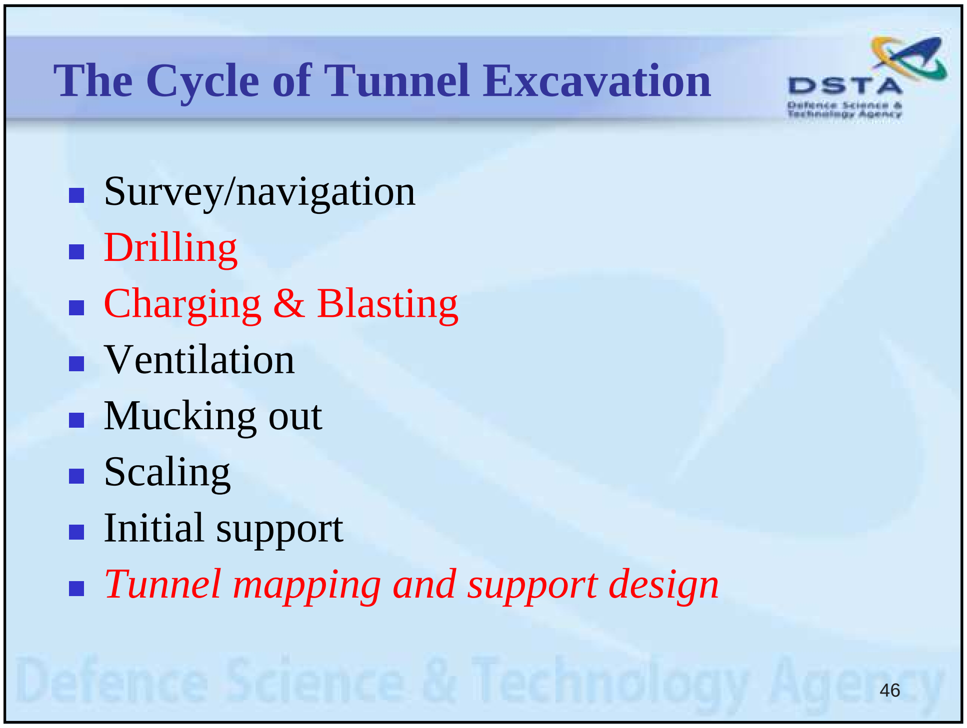


Tunnel Design and Construction



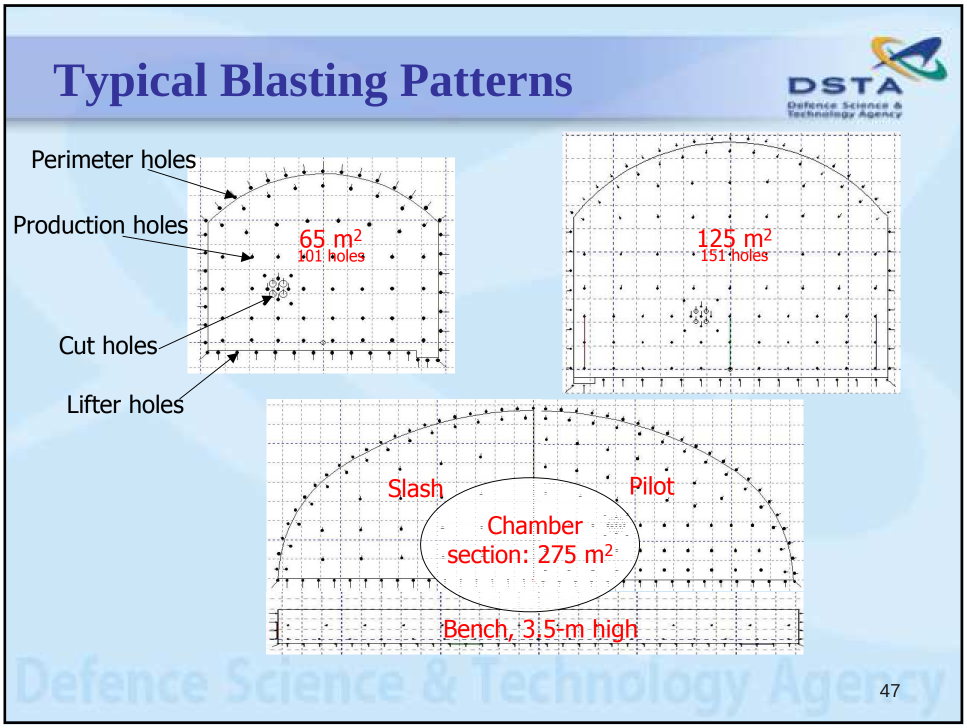
Typical Tunnel Dimensions

Tunnel Parameters	Type I	Type II	Type III
Width, m	10	15	30
Wall height, m	4.5	6.5	8.5
Crown height, m	8.1	11.2	13.5
Area, m^2	62	115	275



The Cycle of Tunnel Excavation

- Survey/navigation
- Drilling
- Charging & Blasting
- Ventilation
- Mucking out
- Scaling
- Initial support
- *Tunnel mapping and support design*



Typical Blasting Patterns

Perimeter holes

Production holes

Cut holes

Lifter holes

65 m²
101 holes

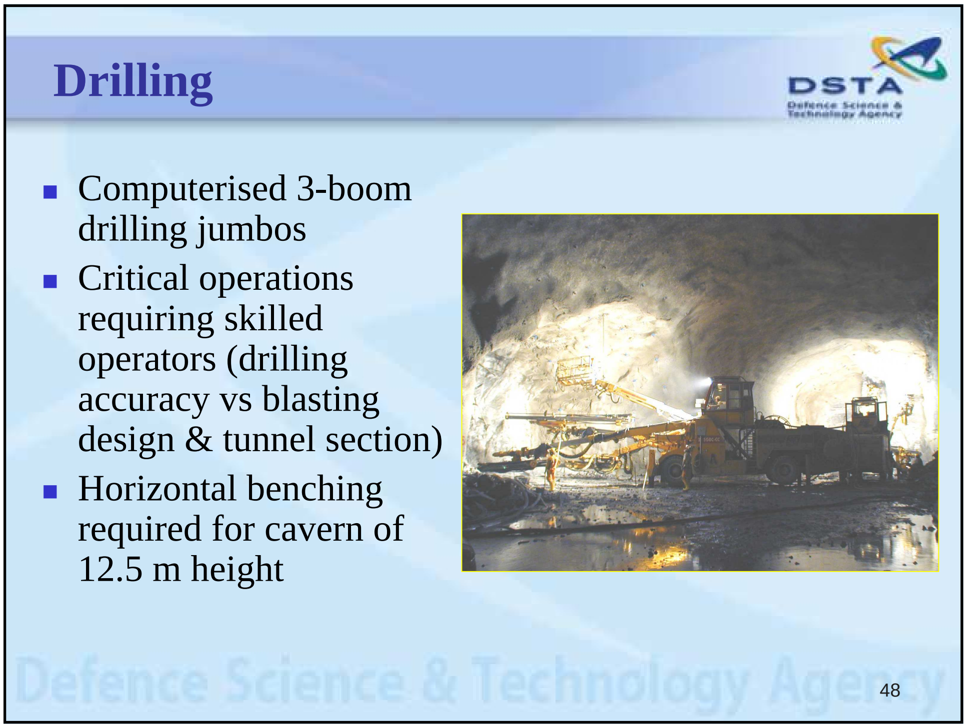
125 m²
151 holes

Slash

Pilot

Chamber
section: 275 m²

Bench, 3.5 m high



Drilling

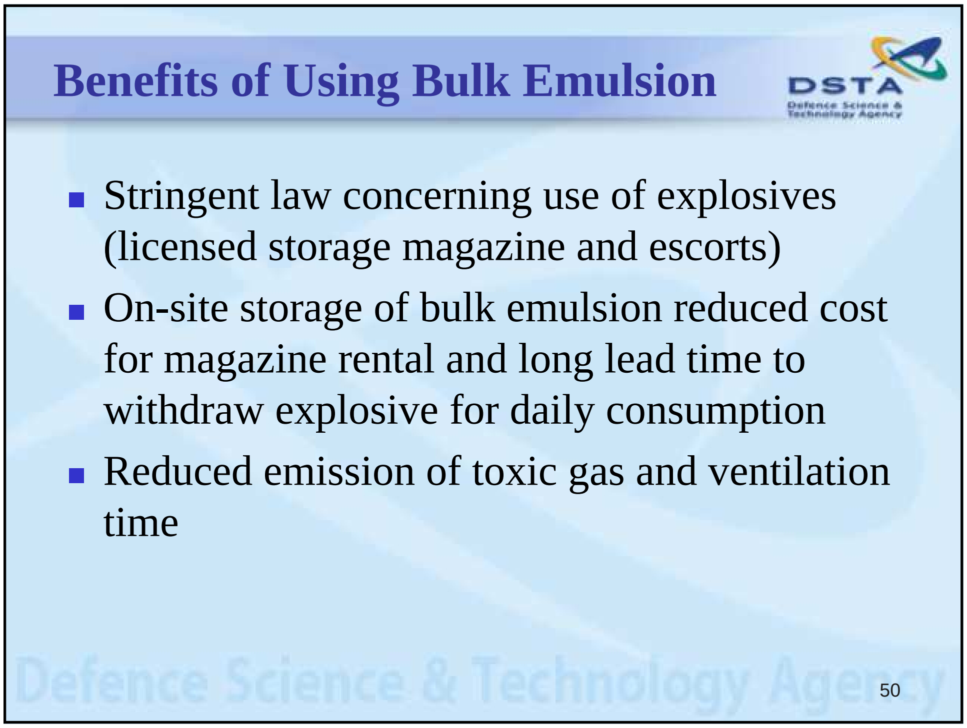
- Computerised 3-boom drilling jumbos
- Critical operations requiring skilled operators (drilling accuracy vs blasting design & tunnel section)
- Horizontal benching required for cavern of 12.5 m height

Production Blasting

- Bulk emulsion
- On-site storage
- Low-risk blasting

Mobile Charging Unit

Storage cavern for detonating devices

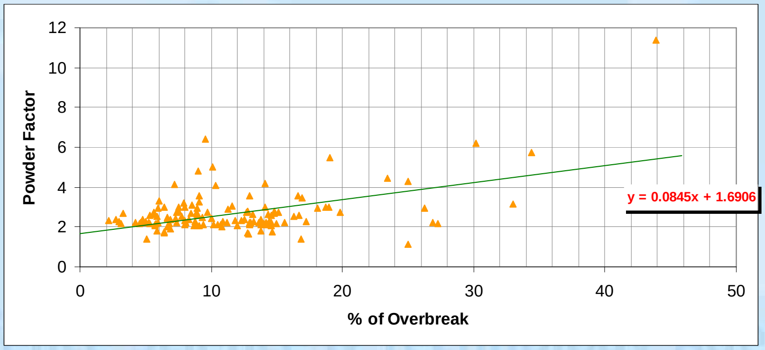


Benefits of Using Bulk Emulsion

- Stringent law concerning use of explosives (licensed storage magazine and escorts)
- On-site storage of bulk emulsion reduced cost for magazine rental and long lead time to withdraw explosive for daily consumption
- Reduced emission of toxic gas and ventilation time

Blasting Efficiency and Overbreak

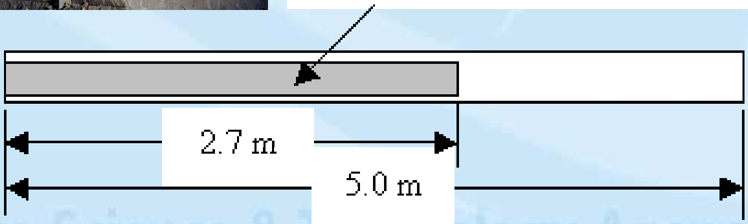
Tunnel Type	% of Overbreak		
	Pilot Phase	Main Phase	Allowance
Type I	13.54	14.38	6.09
Type III	6.732	7.156	4.34



Blasting Design Issues

- “Low risk” blasting design: excessive damage; increased support
- Perimeter blasting generally poor (very few half holes)
- Low cost blasting design: limited experience in bulk emulsion.
- Inefficient benching due to limited bench height (3.5 m) and horizontal drilling
- Blasting vibrations

Trim Blast Using Emulsion



Emulsion in 32 mm PVC pipe at bottom of 51 mm drill hole

Blasting Vibrations

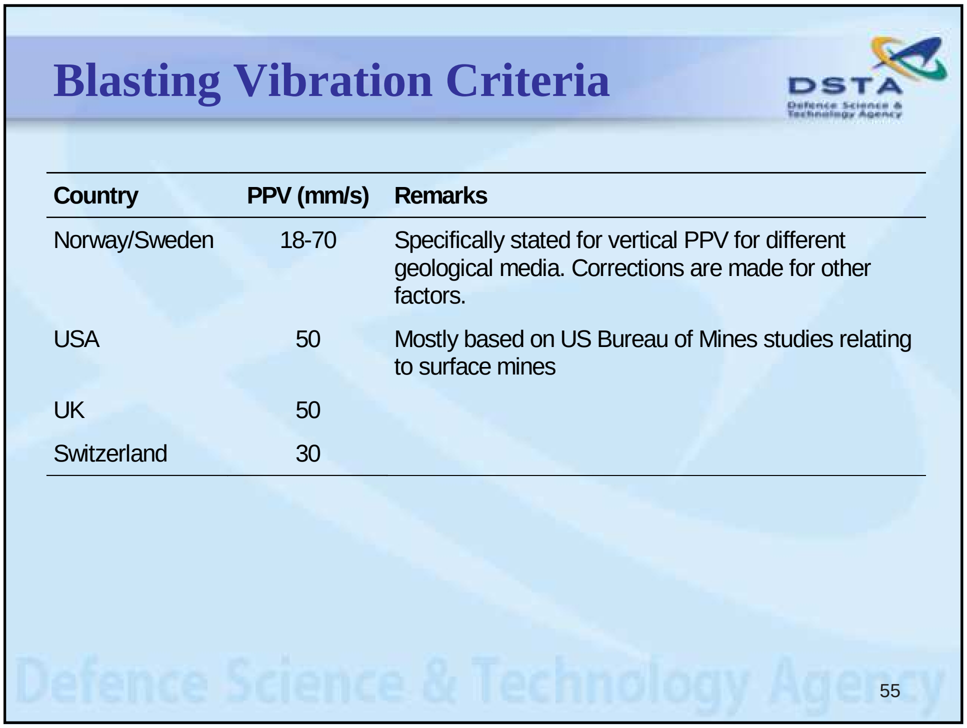
$$V = H\left(\frac{R}{Q^{B}}\right)^{-n}$$

H = constant; B = scaling law;

n = attenuation coefficient

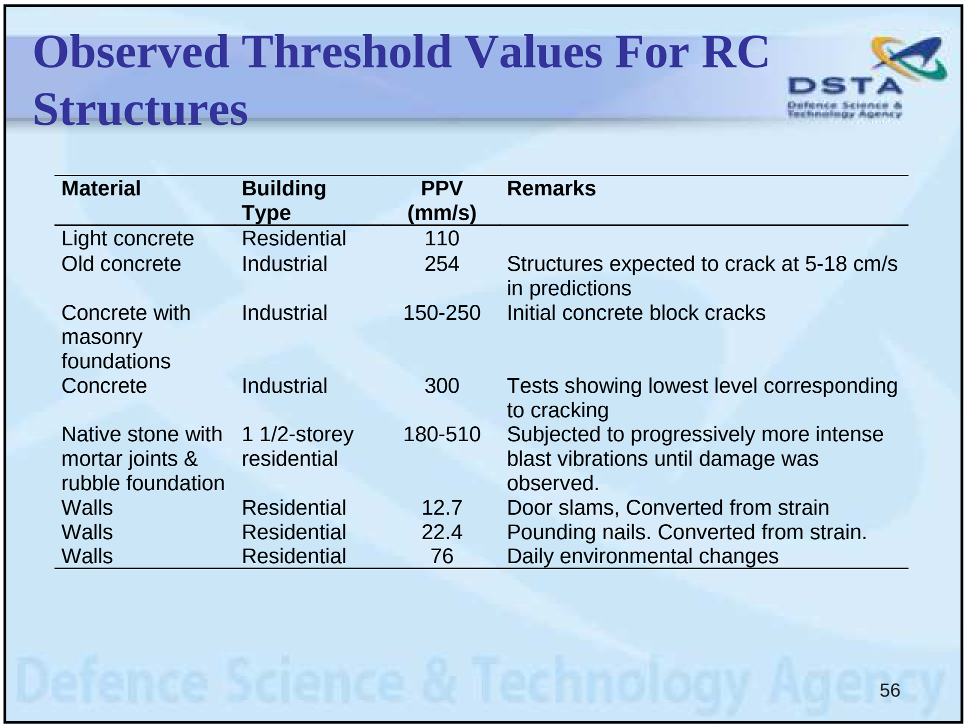
Bukit Timah Granite Test:

$$V = 1099\left(\frac{R}{Q^{1/3}}\right)^{-1.44}$$



Blasting Vibration Criteria

Country	PPV (mm/s)	Remarks
Norway/Sweden	18-70	Specifically stated for vertical PPV for different geological media. Corrections are made for other factors.
USA	50	Mostly based on US Bureau of Mines studies relating to surface mines
UK	50	
Switzerland	30	

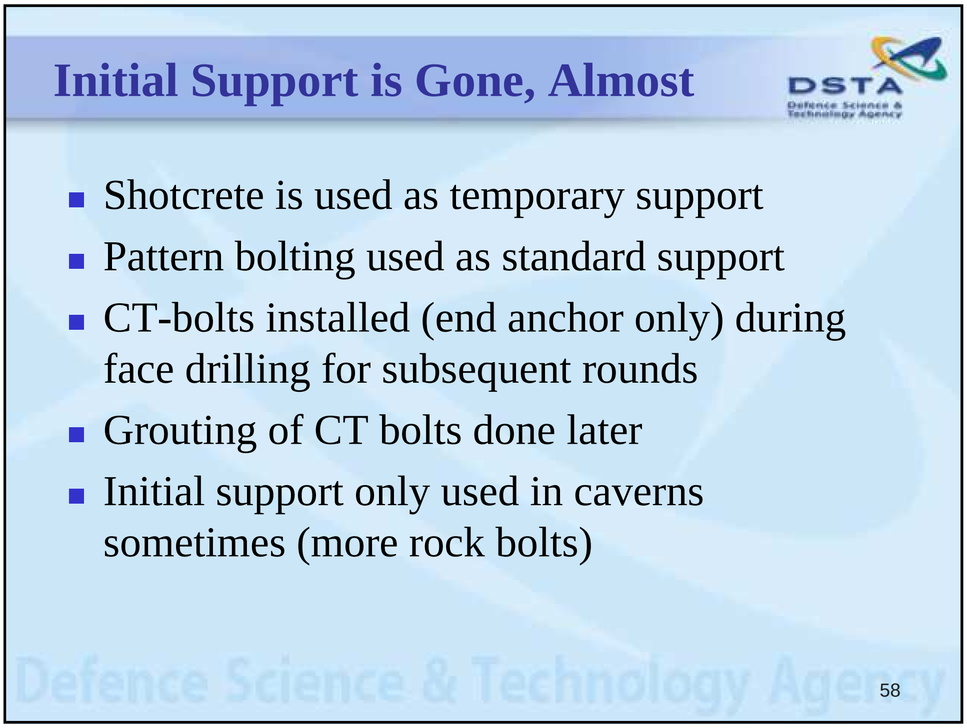


Observed Threshold Values For RC Structures

Material	Building Type	PPV (mm/s)	Remarks
Light concrete	Residential	110	
Old concrete	Industrial	254	Structures expected to crack at 5-18 cm/s in predictions
Concrete with masonry foundations	Industrial	150-250	Initial concrete block cracks
Concrete	Industrial	300	Tests showing lowest level corresponding to cracking
Native stone with mortar joints & rubble foundation	1 1/2-storey residential	180-510	Subjected to progressively more intense blast vibrations until damage was observed.
Walls	Residential	12.7	Door slams, Converted from strain
Walls	Residential	22.4	Pounding nails. Converted from strain.
Walls	Residential	76	Daily environmental changes

Rock Support

(Really **Reinforcement**)



Initial Support is Gone, Almost

- Shotcrete is used as temporary support
- Pattern bolting used as standard support
- CT-bolts installed (end anchor only) during face drilling for subsequent rounds
- Grouting of CT bolts done later
- Initial support only used in caverns sometimes (more rock bolts)

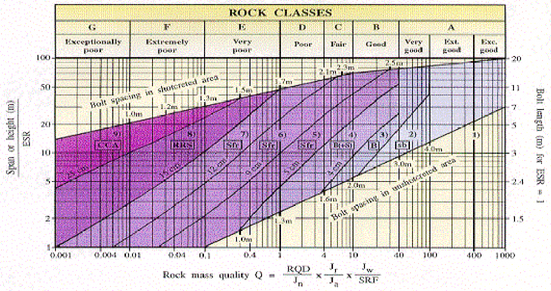
Support Design Using Q-chart

NMT

The Norwegian Method of Tunnelling

TUNNEL SUPPORT DESIGN

Using a new Q-system chart

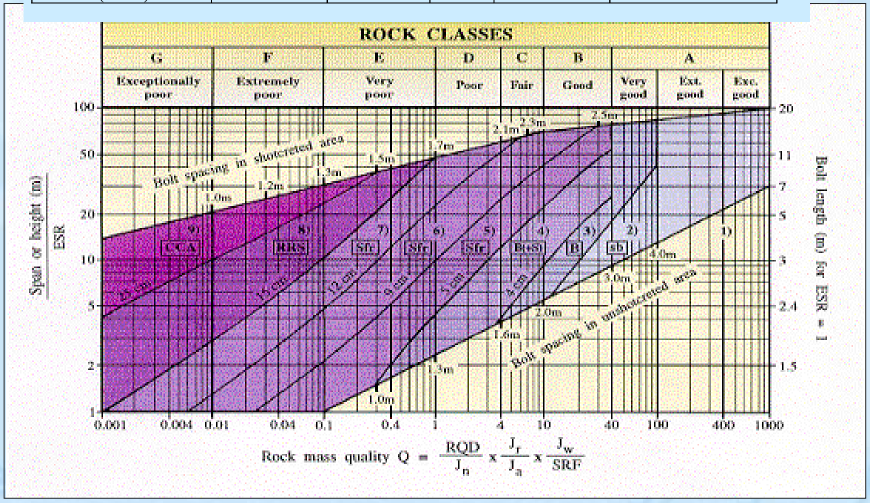


REINFORCEMENT CATEGORIES:

1) Unsupported
2) Spot bolting, sb
3) Systematic bolting, B
4) Systematic bolting, (and unreinforced shotcrete, 4-10 cm), B(+S)
5) Fibre reinforced shotcrete and bolting, 5-9 cm, Sfr+B
6) Fibre reinforced shotcrete and bolting, 9-12 cm, Sfr+B
7) Fibre reinforced shotcrete and bolting, 12-15 cm, Sfr+B
8) Fibre reinforced shotcrete, > 15 cm, reinforced ribs of shotcrete and bolting, Sfr, RRS+B
9) Cast concrete lining, CCA

Q-chart with Energy Capacity for Shotcrete

Rock Class	F	E	D	C, B	A
Energy Absorption, Joules, RDP (40 mm)	560	400	280	200	NA
Energy Absorption, Joules, EFNARC (25 mm)	1400	1000	700	500	NA



Rock Bolt Length

Roof: $L = 2 + 0.15B/ESR$

Walls: $L = 2 + 0.15H/ESR$

L = meters; B = Span; H = wall height;
ESR = Excavation Support Ratio

Quantifying Shotcrete Design

- Shotcrete not normally modelled as structural element in numerical analysis
- Nominal shear strength = 2 Mpa
- Nominal bonding strength = 0.5 Mpa
- Estimate rock wedge volume
- Compare block weight to shear strength and block weight to bonding strength
- ***Shotcrete increasingly accepted as final lining for tunnels***

Effects of Shotcrete

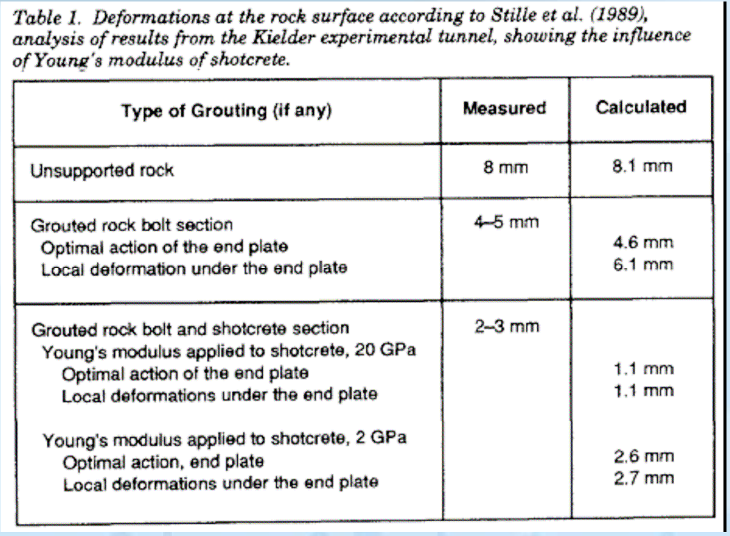


Table 1. Deformations at the rock surface according to Stille et al. (1989), analysis of results from the Kielder experimental tunnel, showing the influence of Young's modulus of shotcrete.

Type of Grouting (if any)	Measured	Calculated
Unsupported rock	8 mm	8.1 mm
Grouted rock bolt section	4–5 mm	
Optimal action of the end plate		4.6 mm
Local deformation under the end plate		6.1 mm
Grouted rock bolt and shotcrete section	2–3 mm	
Young's modulus applied to shotcrete, 20 GPa		
Optimal action of the end plate		1.1 mm
Local deformations under the end plate		1.1 mm
Young's modulus applied to shotcrete, 2 GPa		
Optimal action, end plate		2.6 mm
Local deformations under the end plate		2.7 mm

Source: TUST Vol 7, No 4, 1992

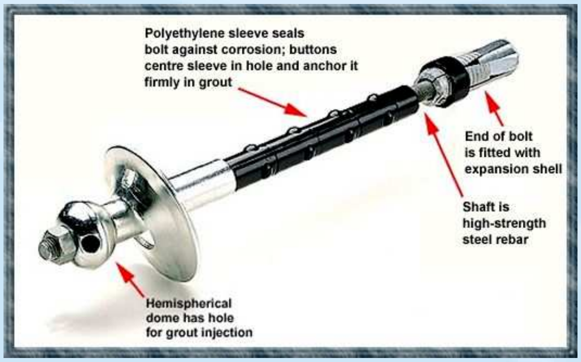
Typical Rock Support

Class	Q	Type I	Type II	Type III
A	>40	Spot	Spot	Spot
		40 mm	40 mm	40 mm
B	10-40	L3(2.4)	L4(2.4)	L5(2.4)
		40 mm	40 mm	50 mm
C	4-10	L3(2.2)	L4(2.2)	L5(2.2)
		40 mm	40 mm	50 mm
D	1-4	L3(1.9)	L4(1.9)	L5(1.9)
		50 mm	50 mm	75 mm
E	< 1	L3(1.5)	L4(1.5)	L5(1.5)
		75 mm	75 mm	100 mm

Note: L3(2.4) = rock bolt length of 3 m at 2.4m center-to-center spacing

Rock Bolts

- 22 mm diameter with 230 KN yield strength and 290 KN failure load



Corrosion protection important for rock bolts

Use of Rock Bolts

- Corrosion protection (polyurethane sleeve, galvanising, cement grout, etc)
- CT Bolts preferred by operators to rebar (bad grout design, lack of physical strength, safety concern, or wrong equipment)
- Pattern bolting or “blind” bolting ?(angled bolts, penetration at rock joints)
- Cost (material cost small component)

Steel Fibre Reinforced Shotcrete

- Wet mix
- Steel fire: 45 kg /m^3
- Alkaline-free accelerators
- Water-cement ratio of about 0.45
- Rebound: 9 – 13%%. Avg = 10%
- Energy capacity test

Energy capacity test results (EFNARC, panel: 600 mm x 600 mm @100 mm thick loaded at centre point. Joules)

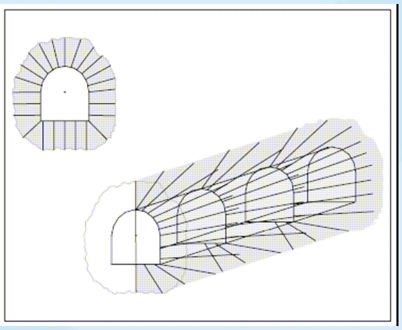
5 mm	10 mm	15 mm	20 mm	25 mm
354	641	866	1042	1180
354	637	862	1047	1198

Grouting

- Used to minimise water seepage, not to stop water completely
- Probe holes of 25 m drilled into face when necessary
- Pre-grouting when flow in three boreholes exceed 15 l/min
- Grouting pressure usually at 30-50 bar (equivalent to 30-50 m water pressure)

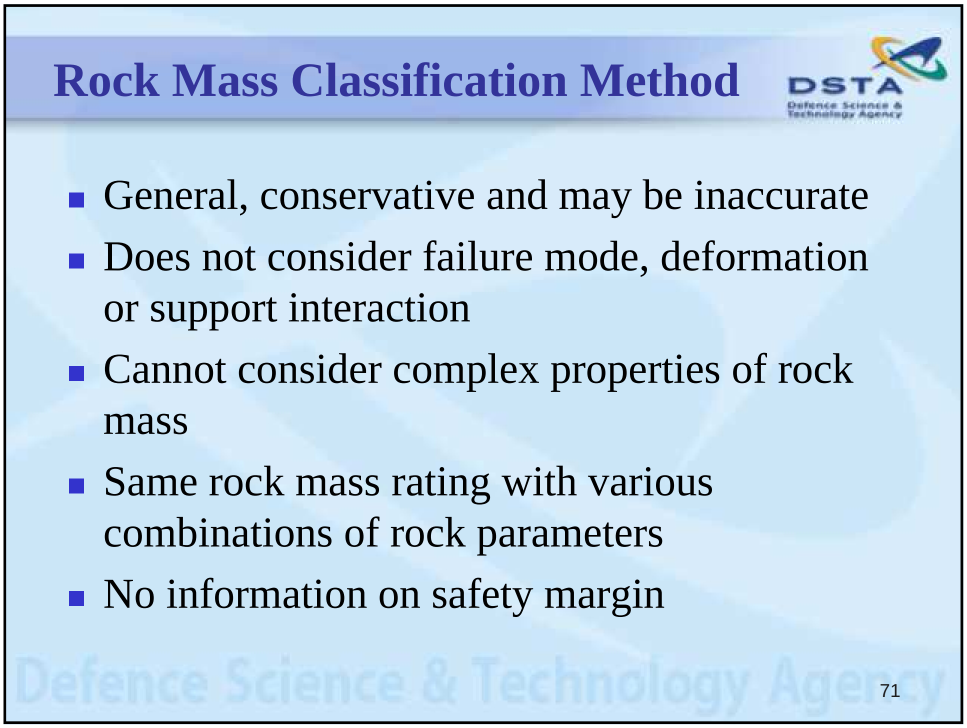
Grouting Principles

- Pre-grouting much more effective than post-grouting
- Good penetration (joints aperture and cement type)
- Pressure important (high pressure is better)
- Overlapping of grouting zones (> 5m)
- Thickness must be larger than rock bolts (look out angles).



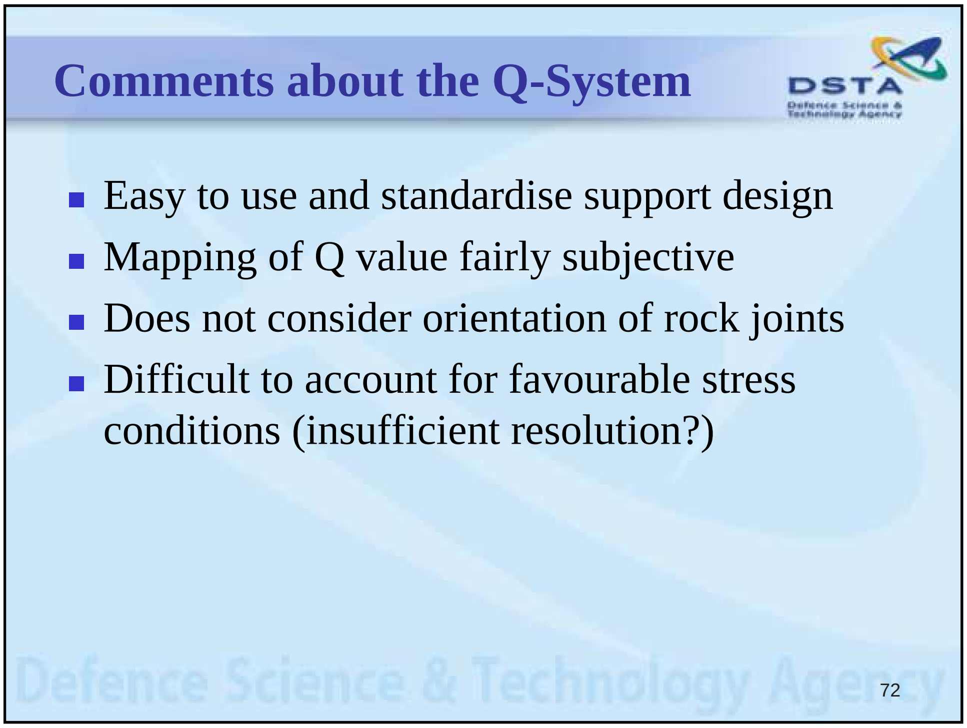
Excessive Water Seepage

- Normal cement grouting not effective
- Hot bitumen grouting has been used to good effect in controlling water more than 20,000 l/min.
- Water stoppage achieved within hours in dam foundation operations
- Cement grout usually follows to impart strength after initial “plugging” of water seepage.



Rock Mass Classification Method

- General, conservative and may be inaccurate
- Does not consider failure mode, deformation or support interaction
- Cannot consider complex properties of rock mass
- Same rock mass rating with various combinations of rock parameters
- No information on safety margin



Comments about the Q-System

- Easy to use and standardise support design
- Mapping of Q value fairly subjective
- Does not consider orientation of rock joints
- Difficult to account for favourable stress conditions (insufficient resolution?)

Tunnel Geometry Design

- Minimum competent rock cover of 20 m or 1.5 times span
- Empirical rule of 0.2 x tunnel span for arch height results in significant unused tunnel space
- Does not take into consideration of favourable horizontal stresses

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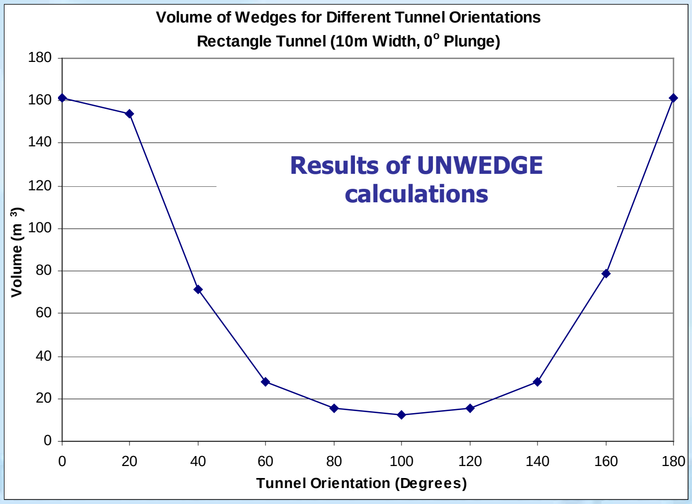
Optimisation of Rock Support

- Numerical modelling
  - Geological representation
  - Realistic rock mass properties
  - Tunnel stability criteria (is deformation a good criterion to use in hard rock?)
- Instrumentation and monitoring
  - Use of results
  - Absolute deformation vs measured deformation vs supported deformation

Effects of Joint Orientation

Tunnel Orientations vs Wedge Sizes

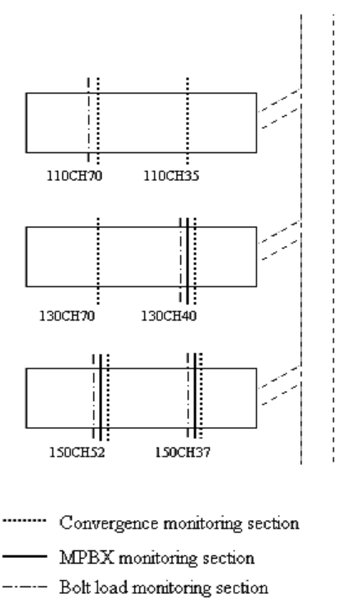
Based on Joint Data from Acoustic Imaging BH12: (136/57) (66/73) (280/44)



Results of UNWEDGE calculations

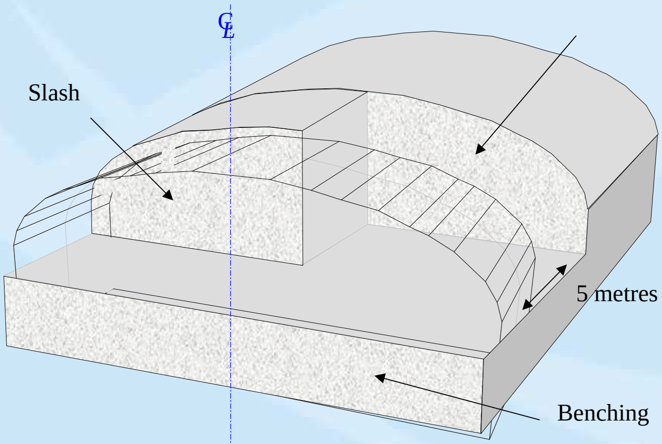
Instrumentation and Monitoring

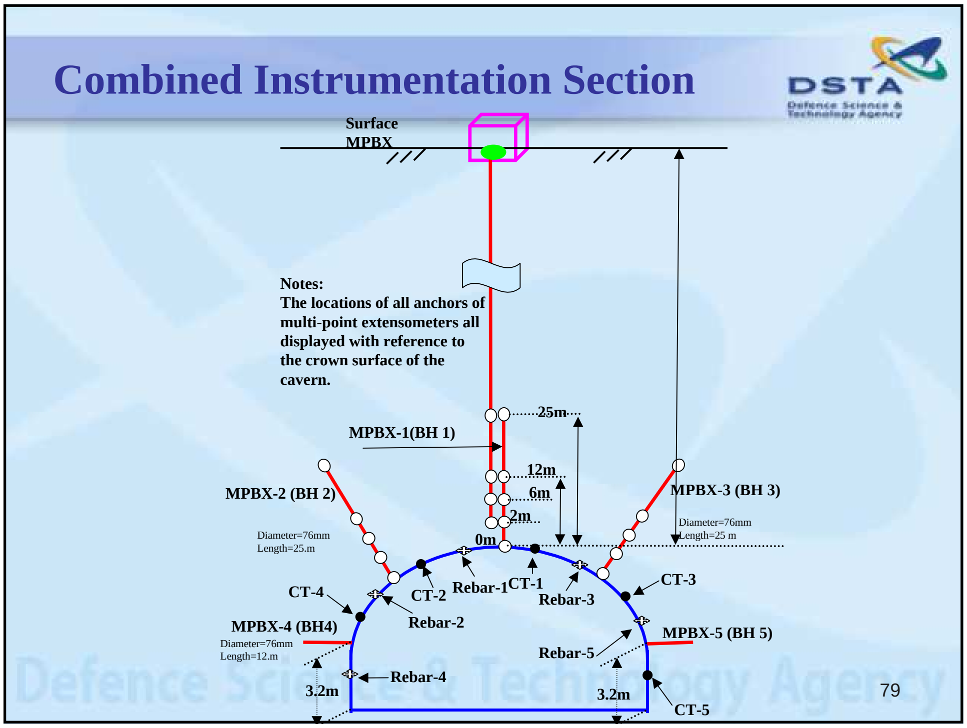
Instrumented Cavern Sections



- Instrumentations & monitoring performed during & after construction:
    - Borehole extensometer
    - Convergence (tape)
    - Bolt load (strain gauges)

Cavern Excavation Sequence

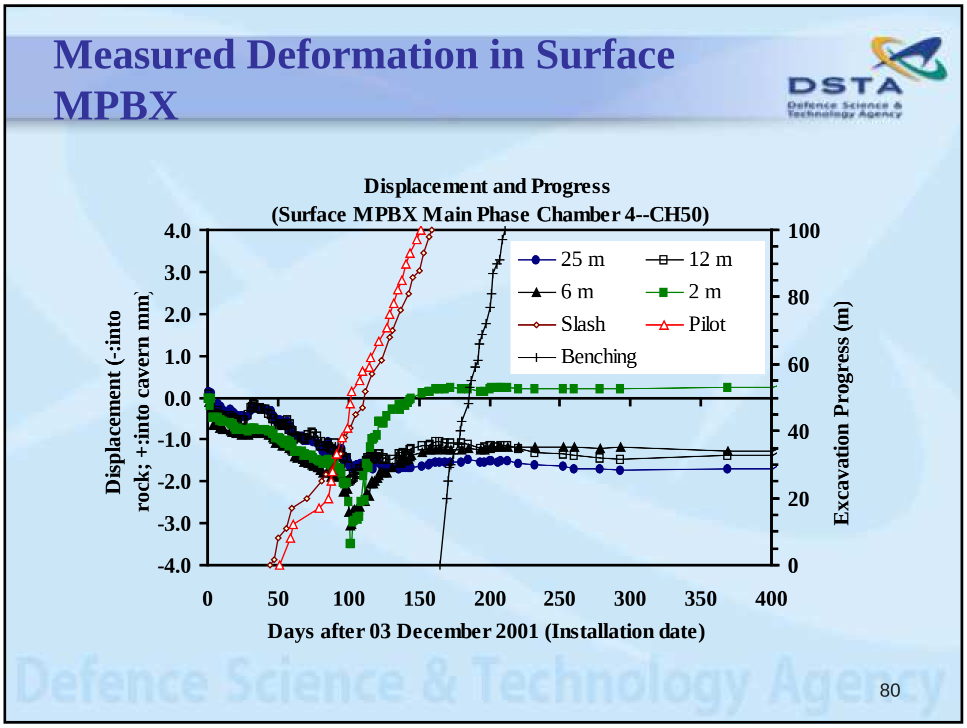




Combined Instrumentation Section

Surface MPBX

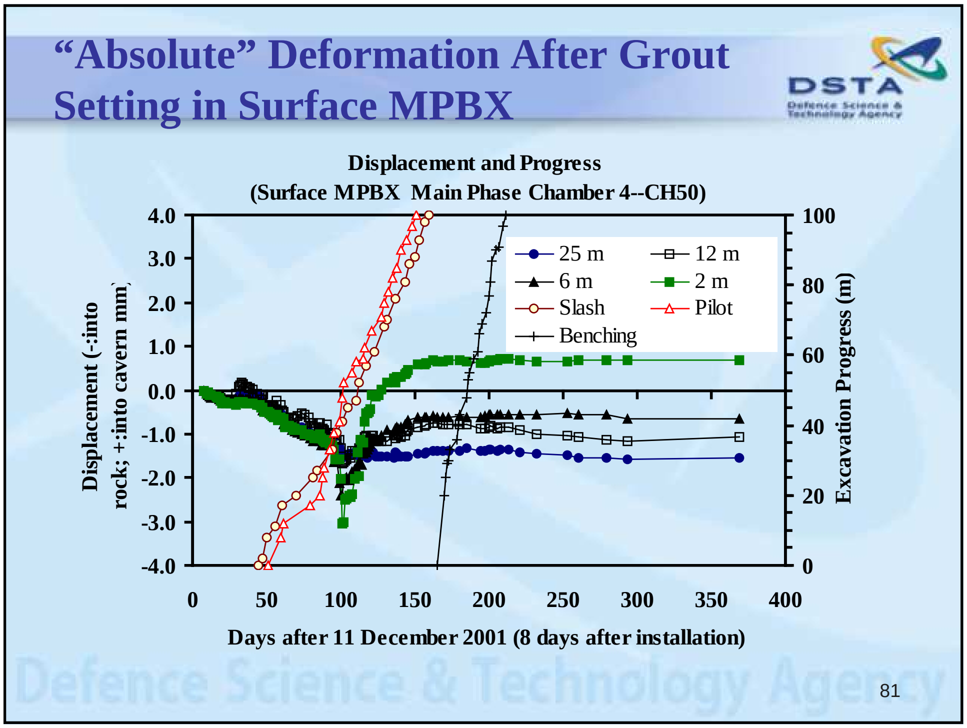
Notes:
The locations of all anchors of multi-point extensometers all displayed with reference to the crown surface of the cavern.



Measured Deformation in Surface MPBX

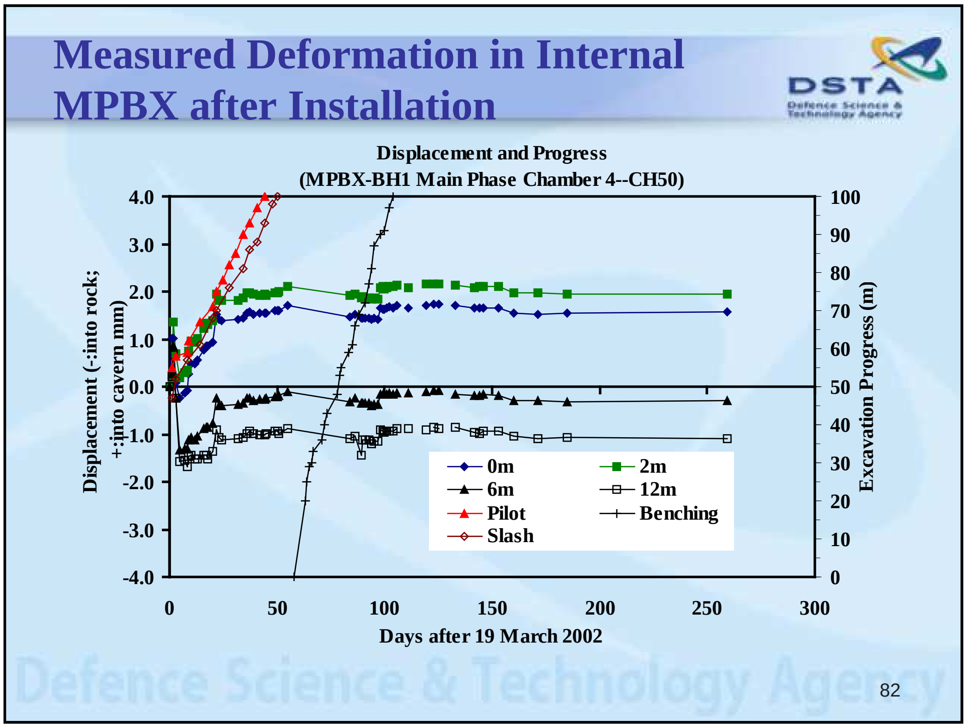
Displacement and Progress
(Surface MPBX Main Phase Chamber 4--CH50)

“Absolute” Deformation After Grout Setting in Surface MPBX

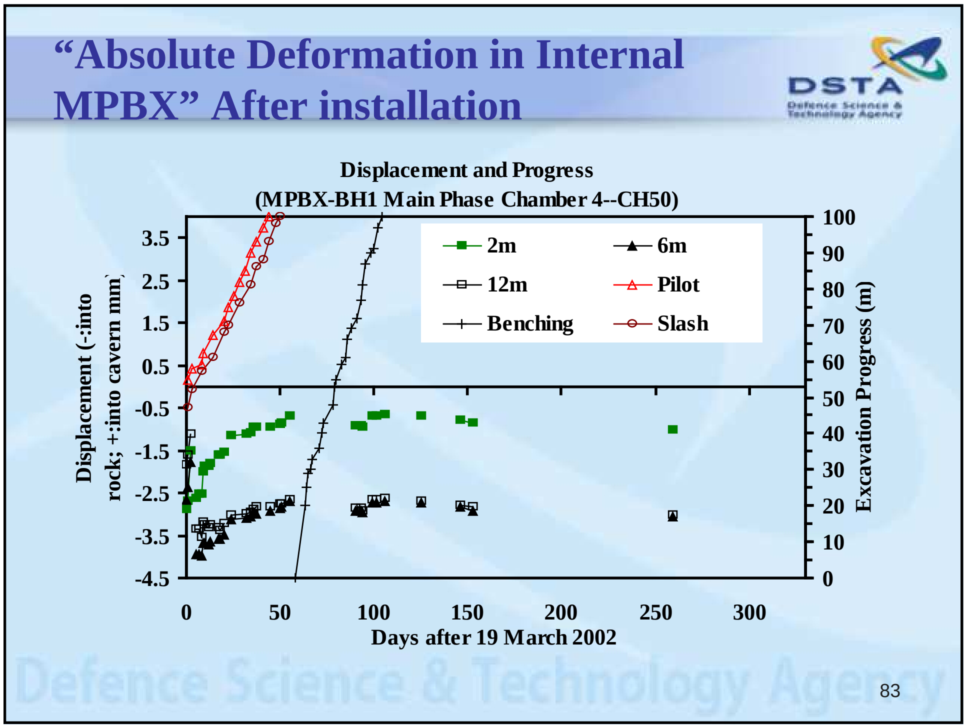

Displacement and Progress
(Surface MPBX Main Phase Chamber 4--CH50)

Days after 11 December 2001 (8 days after installation)

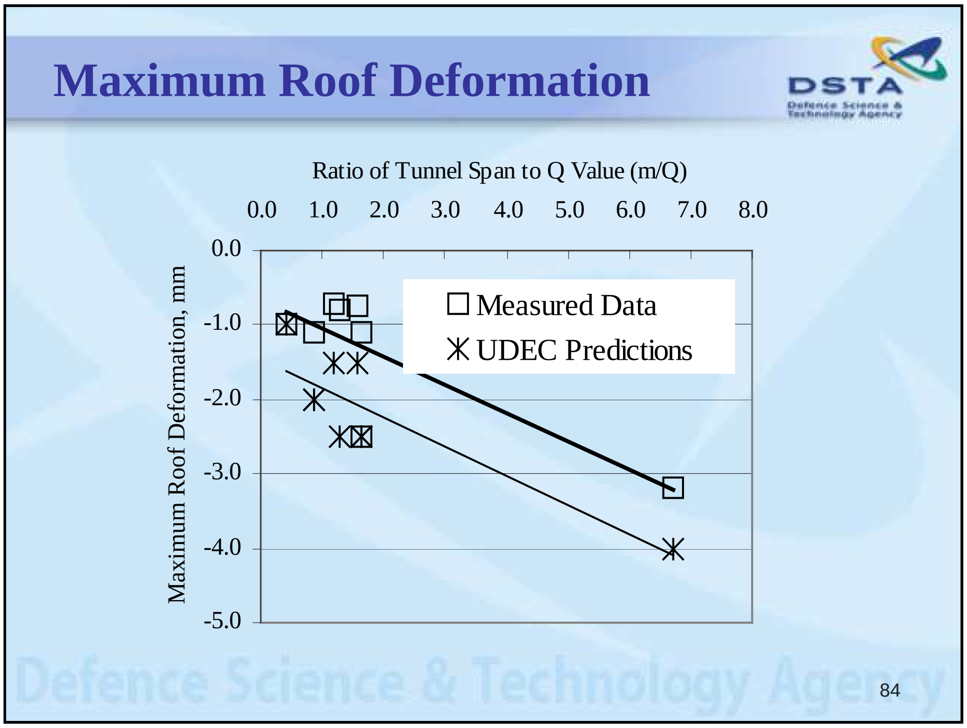
Measured Deformation in Internal MPBX after Installation


Displacement and Progress
(MPBX-BH1 Main Phase Chamber 4--CH50)

Days after 19 March 2002



"Absolute Deformation in Internal MPBX" After installation

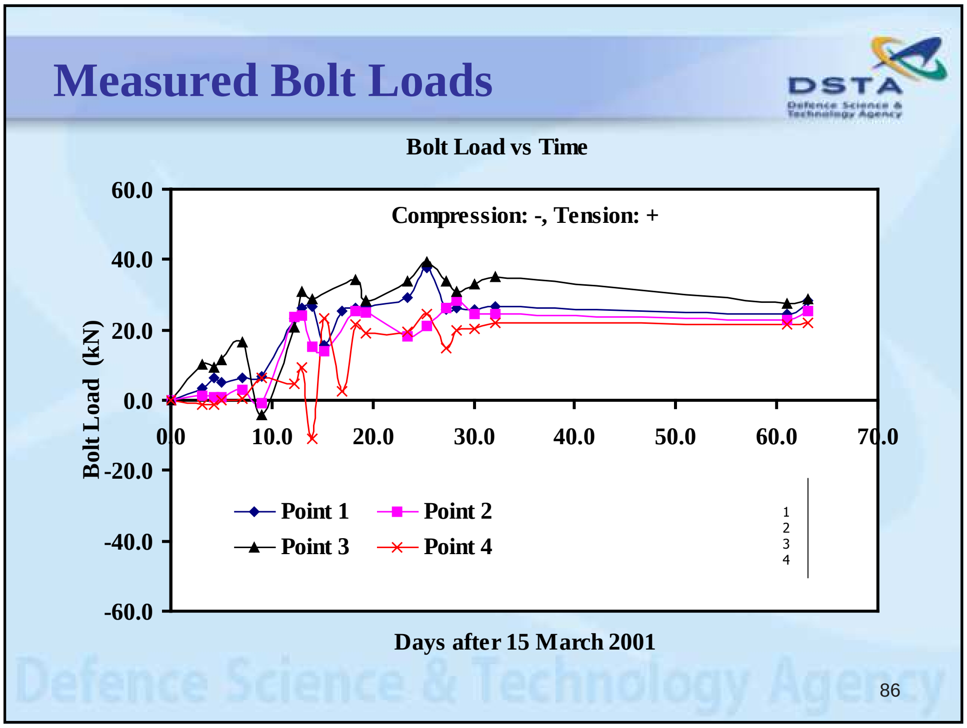


Maximum Roof Deformation

Summary of Deformation Measurements

- Similar patterns of deformation between internal MPBX and surface MPBX
- Upwards movement of chamber crown observed, peaking when top heading passed measurement position and eventually stabilising at less downward movements
- Inward movement of chamber walls consistently observed

Measured Bolt Loads



Rock Bolts Performance

- Bolt load tends to change considerably before stabilising
- No consistent pattern of maximum bolt loading due to grouting
- Recorded bolt load about 10-25% of design load
- Possible to reduce bolt density and length

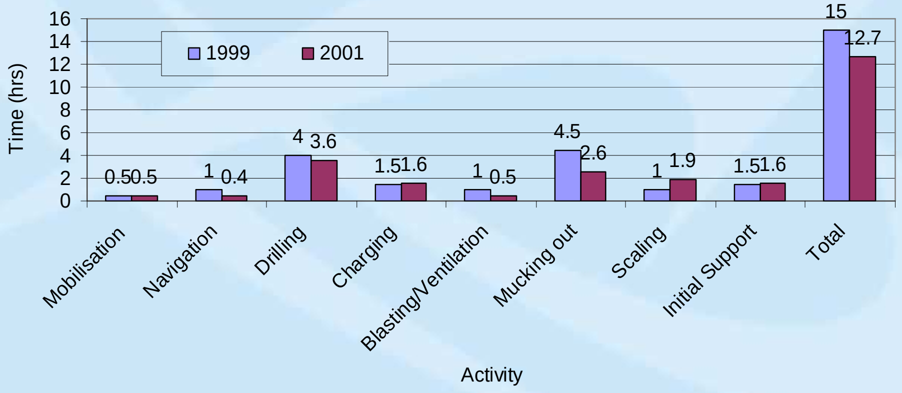
Implications for Rock Support

- Rock reinforcement for the cavern roof could be reduced
- Further optimisation of cavern shape is possible (reduced crown height means less excavation cost)

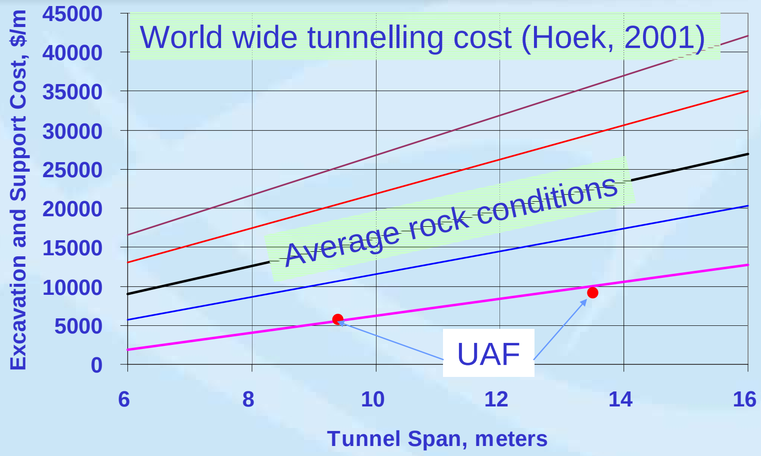
Comparison with Gjovik Stadium in Norway (after Broch et al. 1996)

Rock Conditions & Bolt Parameters	GjØvik Stadium, Norway (Based on Broch at el. 1996)	Singapore Site
Typical Rock Mass Quality	1 - 30	4 - 36
Vertical Stress, MPa	1	2-3
Max Horizontal Stress	3.5	8.2
Minimum Horizontal Stress	2	4.6
Ratio of Hori. to Vertical Stress	2-3.5	2-3
Tunnel/cavern span, meters	61	10 – 30
Type of Rock Bolts	Fully grouted rebars	Fully grouted CT-bolts
Lengths, meters	6 m (with alternating 12-m long cables	3-6 m
Spacing, meters	2.5 m x 2.5 m	1.5 – 2.4
Bolt Capacity, KN	220	250
Minimum Measured Loads, KN	1 – 1.5	3 - 12
Typical Measured Loads, KN	30 - 60	20- 60
Typical Load Percentage	13 – 27%	8 – 24%
Maximum Measured Load, KN	87	70
Max Load Percentage	40%	28%

Back to the Tunnel Cycle



Comparison of World-wide Cost



- Competitive cost in Singapore due primarily to a) large tunnel sections; b) good rock; and c) low labour cost

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Conclusions

- No surprises in construction due to good site investigations
- Bulk emulsion explosives proven very beneficial for safety and productivity
- High horizontal stress key factor for stability of large-span rock caverns
- For favourable horizontal stresses, support design using Q-system could be further optimized

“Practical Rock Engineering”

- Very good course notes by Evert Hoek.
- Free download available at:

www.rocscience.com/hoek/PracticalRockEngineering.asp

4th Asian Rock Mech Symposium

Short Courses

- ***Rock Failure Process Aanalysis (RFPA)***, by Prof Tang, 7 Nov 06
- ***Borehole Stability, Earth Stresses and Drilling***, by Prof Dusseault, 6-7 Nov 2006

Workshops

- ***Rock Dynamics***, 7 Nov 06 (AM)
- ***Underground storage facilities***, 7 Nov 2006 (PM)

Website: www.arms2006.org

Society for Rock Mechanics & Engineering Geology (Singapore)

- Formerly Engineering Geology and Rock Mechanics Group under TUCSS since 1998
- Registered as new society in July 2006 for better focus on rock mechanics and engineering geology
- Affiliated to ISRM and IAEG
- First AGM to be held on 27 Sept 06
- Contact: Ms An Xinmei.Email: ANXI0001@ntu.edu.sg