Dynamic Response and Tunnel Damage from Explosion Loading

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Explosives Storage Safety

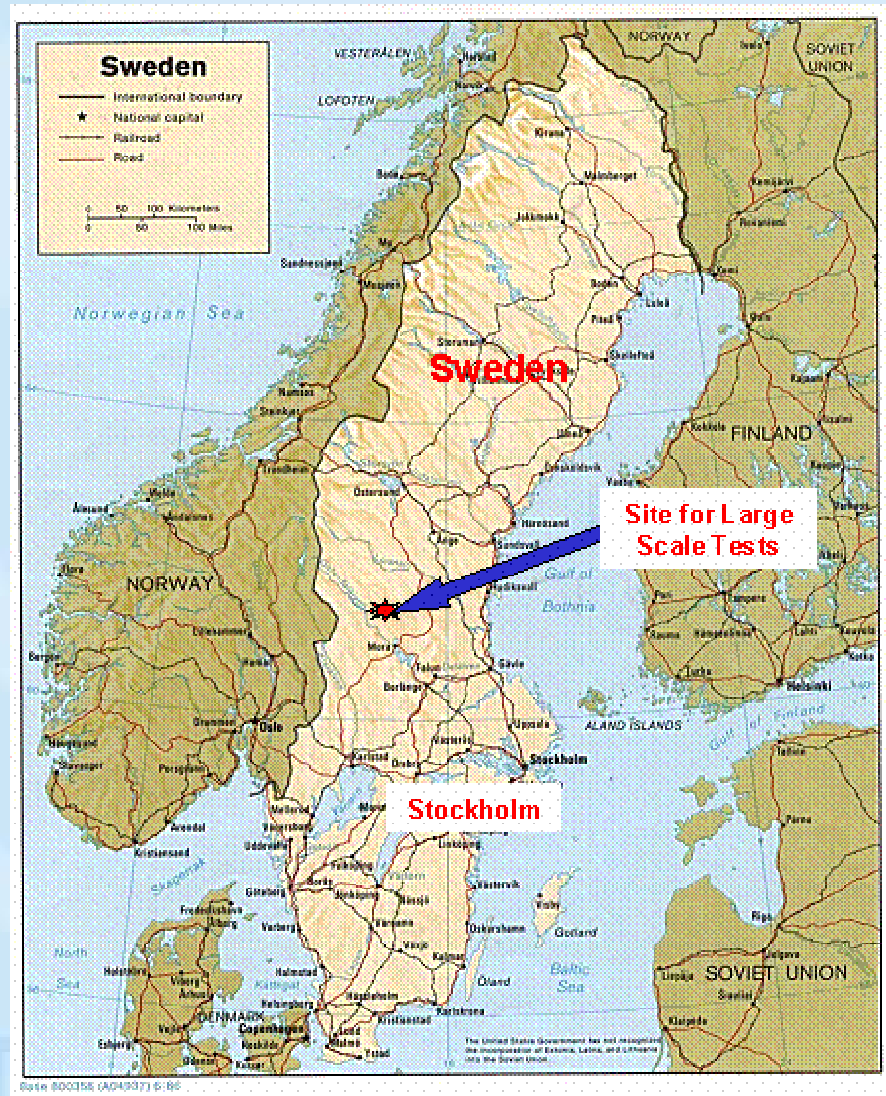
- Design must consider accidental explosion (airblast, ground shock, debris, fire)
- Internal Safety
  - Chamber separation
  - Prevention of sympathetic detonation
- External Safety
  - Inhabited buildings
  - Public transport route
  - Workshops

Large-scale Tests for Underground Storage

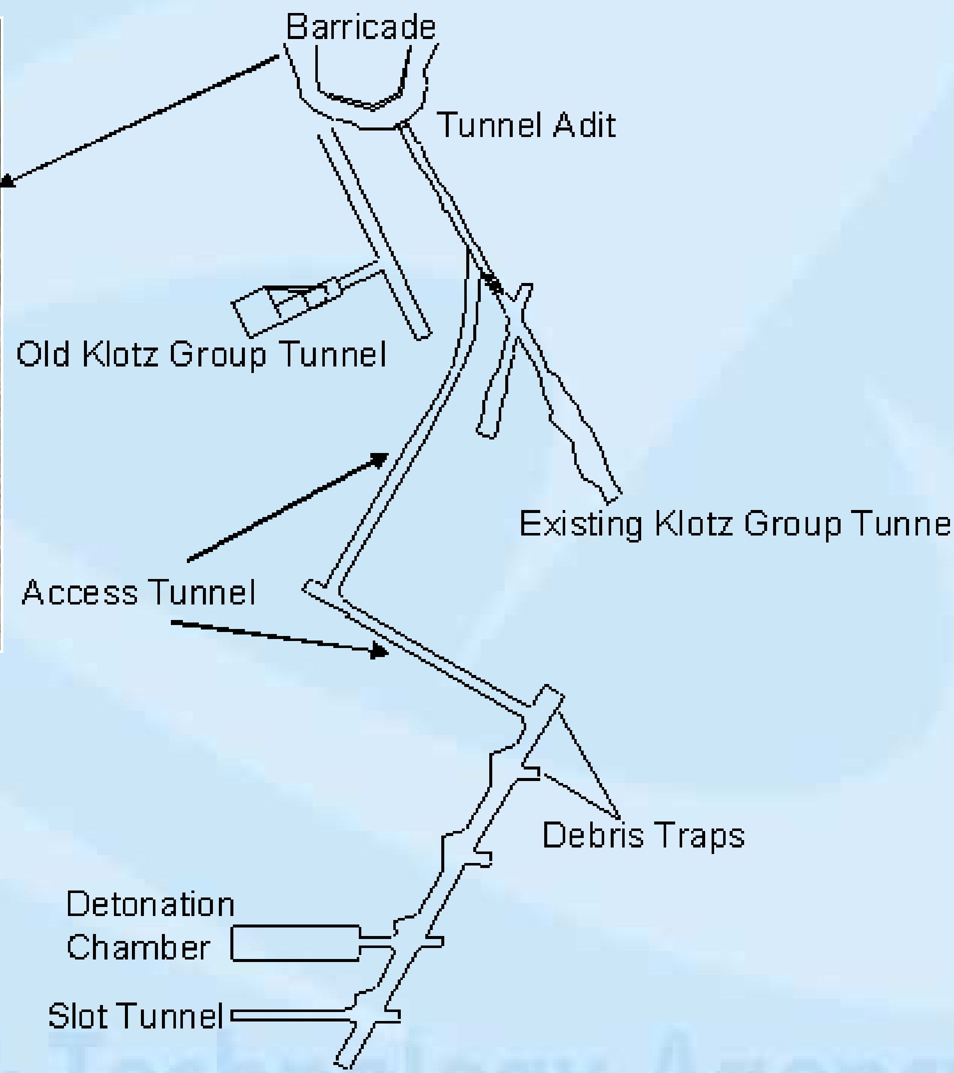
Collaboration with Swedish Defence Research Agency and Armed Forces HQ

Validation of underground facility design

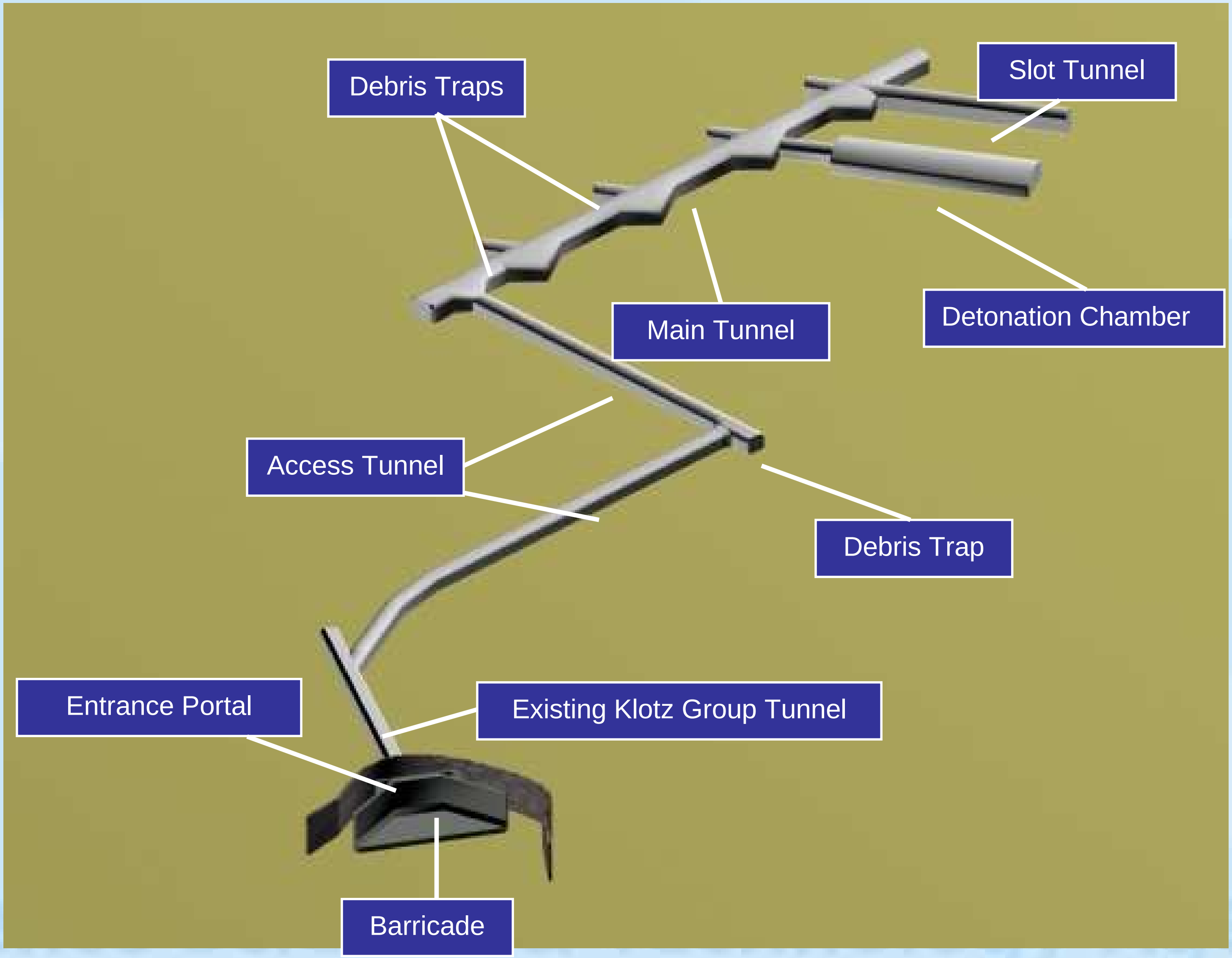
- Airblast propagation
- Door pressure and response
- Ground shock,
- Debris hazards
- Response of tunnels (at criterion distances)



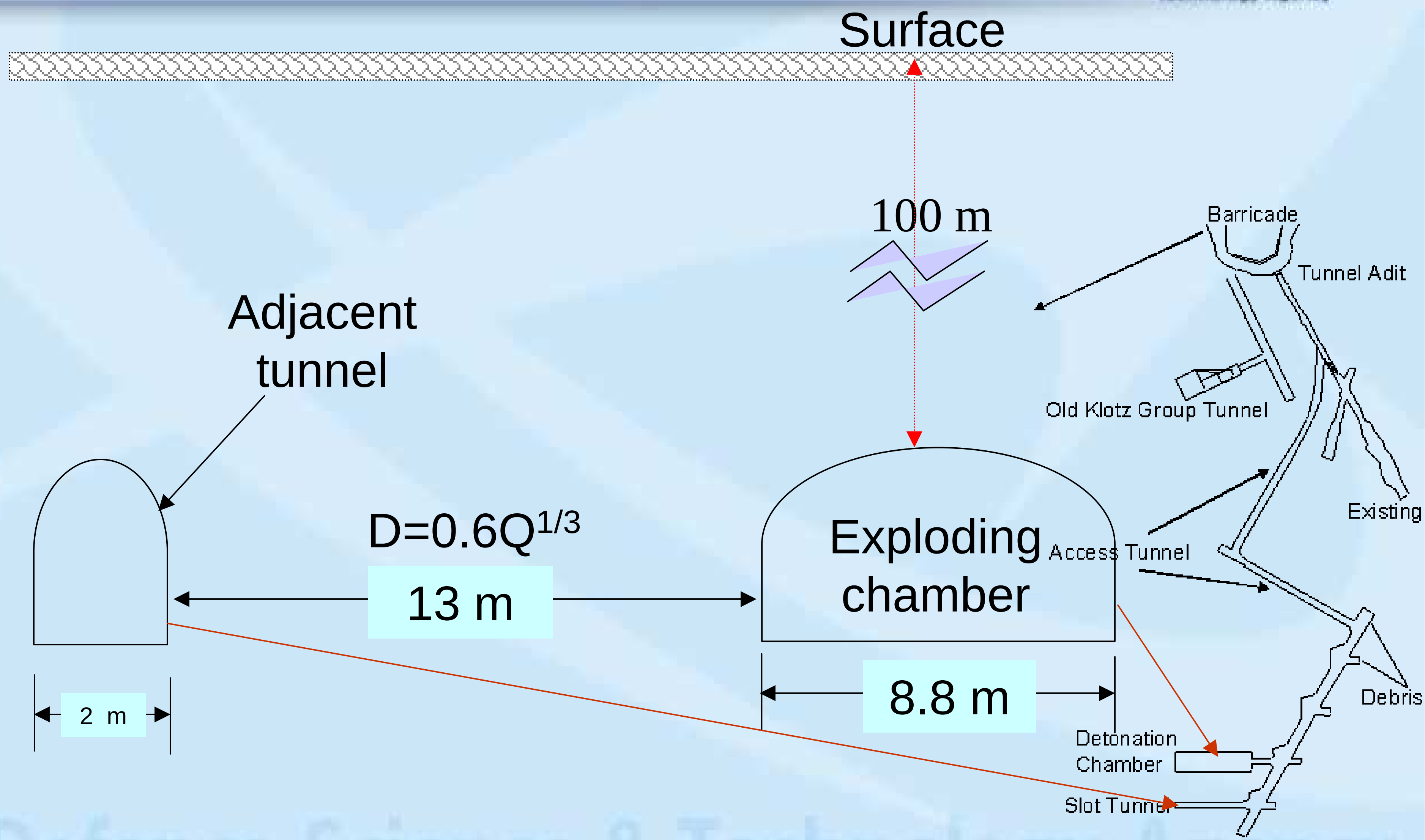
Layout of Test Facility



Test Facility Layout – 3D View



Chamber Sections



Considerations in Tunnel Design

- 10-ton explosives charge weight
- Fragment loading (155 mm rounds)
- Repeated blasts (3-4 year programme)
- Safety considerations (need to go into tunnel after test)

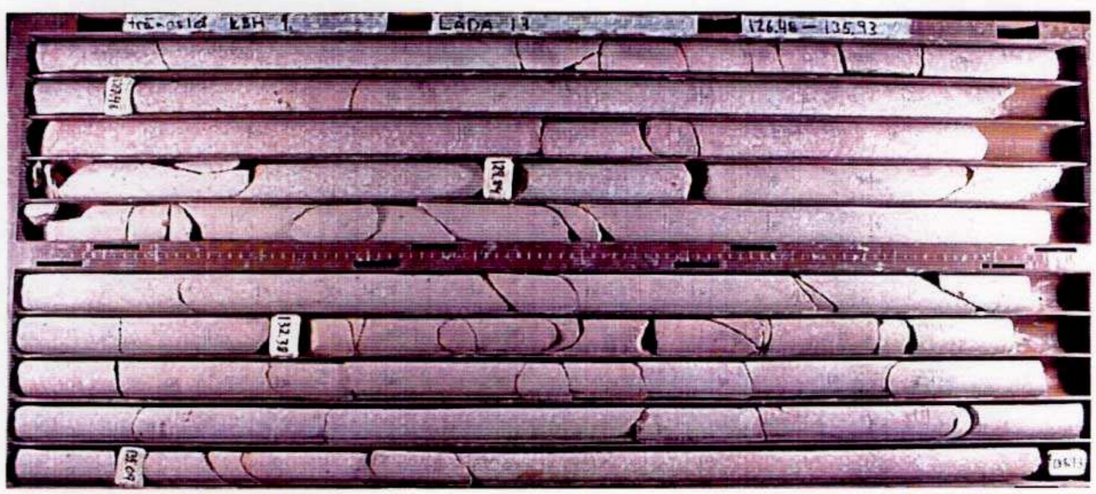
Requirements for Tunnel Design

- Rock mass properties (can't take everything for granite!)
- Ground shock prediction
- Tunnel damage criteria (if you know what it means)

Rock Mass Properties

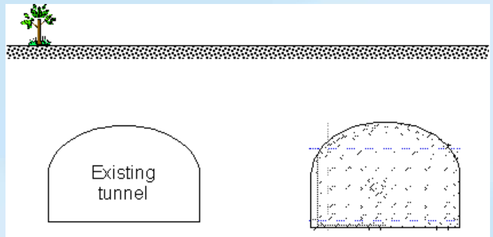
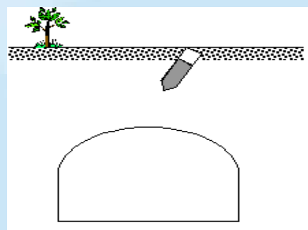
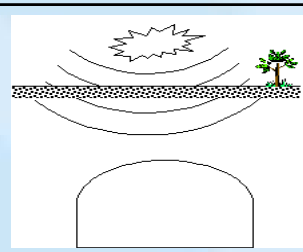
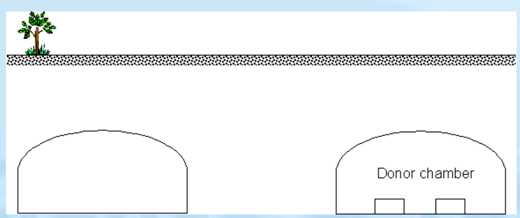
Rock type	Red porphry syenite with grey granitic intrusion
Density	2620 kg/m^3
Uniaxial compressive strength	200-250 MPa
Uniaxial tensile strength (based on point load tests)	12.5 – 17.5 MPa
Rock mass quality	Avg Q value: 15-20

Trängslet KBH 1. Låda 13. Meter 126.48-135.93



Ground Shock Prediction

Sources of Ground Shock

Sources	Illustration	Characteristics
Tunnelling / mining – blasting		Fully coupled charge Low charge weight Multiple delays Repetitive blasting
Conventional weapons – penetration bomb		Limited charge weight Fully coupled or contact explosion Penetration & Cratering effects
Nuclear weapons		Largest charge weight (kt or Mt) Large displacement Generally indirect-induced shock
Ammo storage – accidental explosion		Low probability Large charge weight Low loading density

Empirical PPV Equation

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

H = constant; B = scaling law;

n = attenuation coefficient

Parameters for Coupled Explosions

$$H = (500/C^{2.17})/(\rho C), \text{ mm/s}$$

Rock Type	Rock Mass Density, ρ, kg/m3	Seismic Velocity, C, m/s	Initial Value, H (mm / sec)	Attenuation Coefficient, n D < 6	Attenuation Coefficient, n D > 6
Good	> 2600	5100-6000	5000	1.5	1.2
Fair	2300-2600	4100-5100	4000	1.8	1.5
Poor	< 2300	3500-4100	3000	2.3	1.8

$D = R/Q^{1/3}$, scaled range, $m/kg^{1/3}$

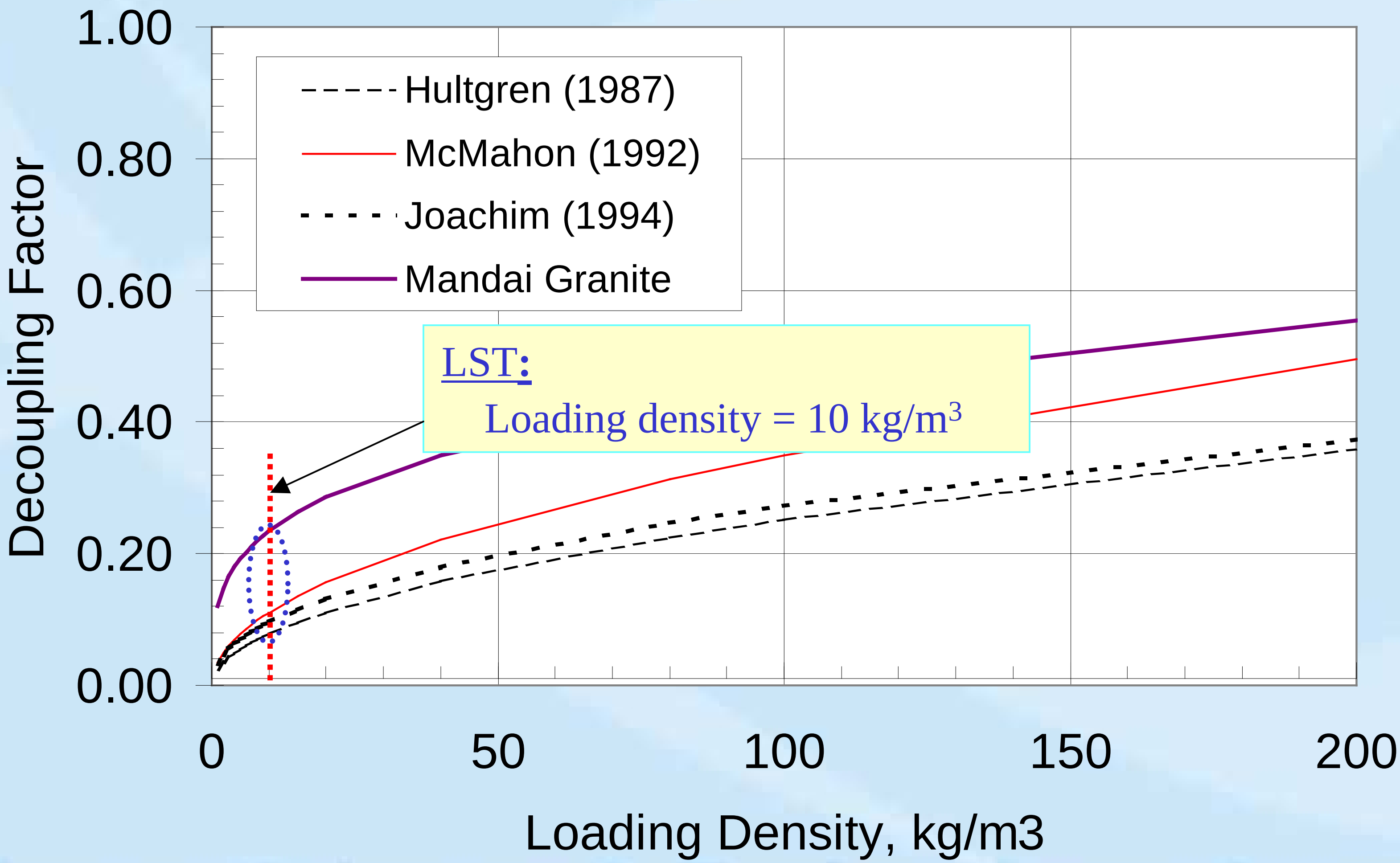
Conservative estimate for spherical charges

Correction Factors for PPV

- Charge geometry (distributed vs concentrated charge)

- Decoupled explosions (explosives not in full contact with rock)

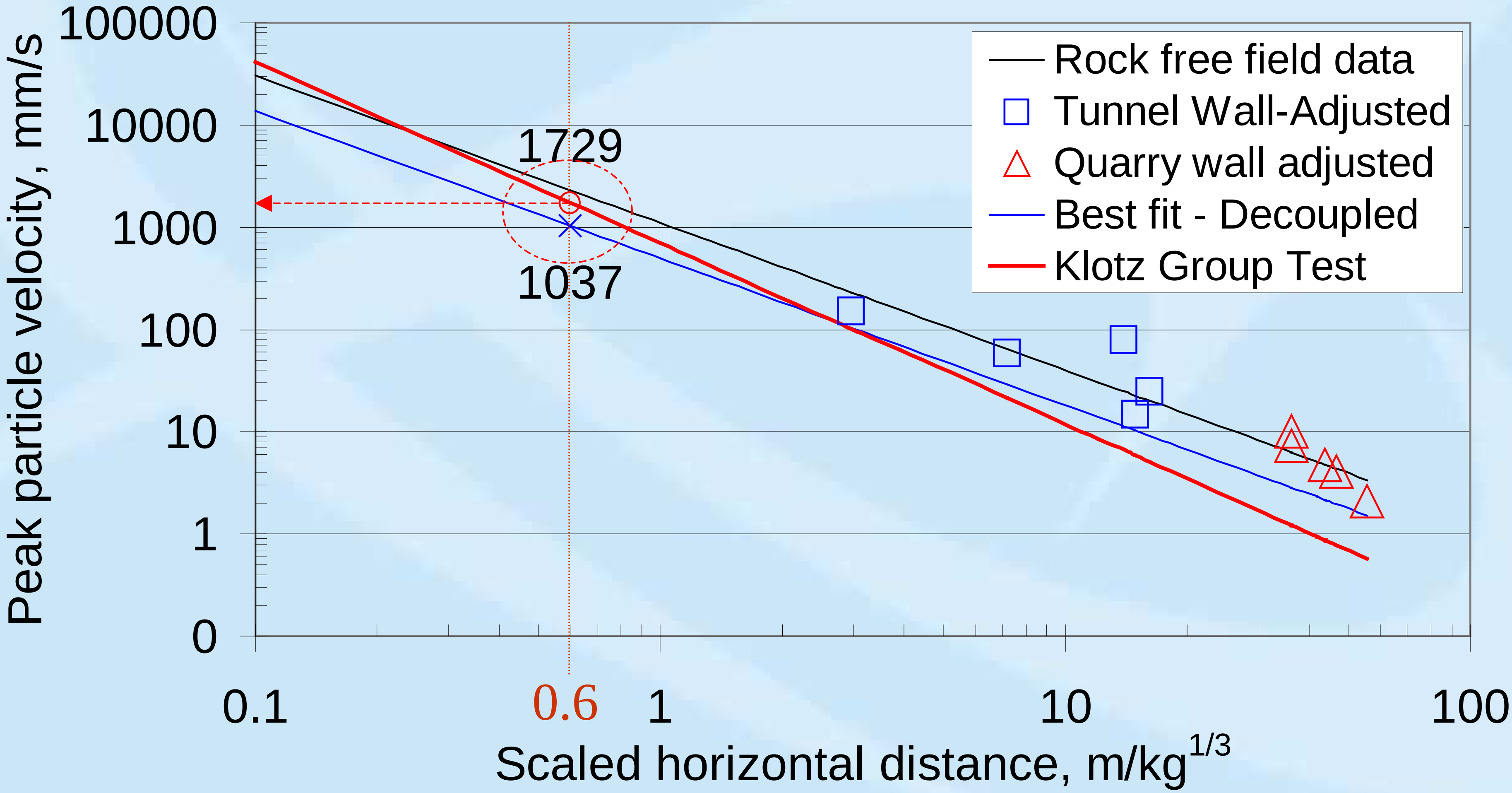
PPV Correction Factor for Decoupled Explosions



PPV Prediction - Slot Wall

Charge weight	10000 kg
Fully coupled PPV	$5000(R/Q^{1/3})^{-1.5}$ $= 5000(14/10000^{1/3})^{-1.5}$ = 10,760 mm/s
PPV correction for charge geometry	0.6 – 0.8
Decoupling factor	0.116 – 0.23
Predicted PPV for slot wall (incipient)	10,760x0.6x(0.116-0.23) = 748-1,485 mm/s

Ground Shock Curves

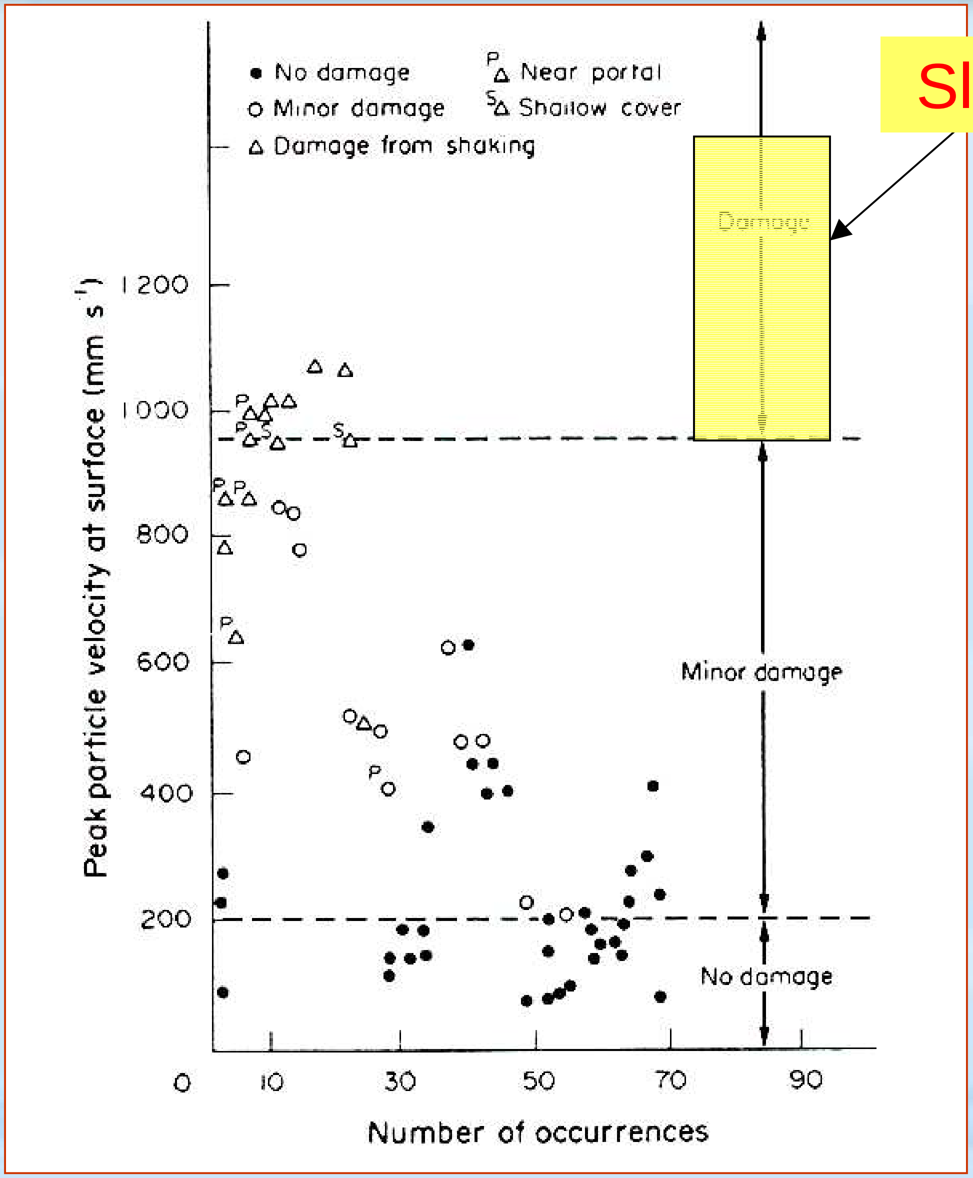


Tunnel Damage – What does it mean?

Damage of Unlined Tunnels – a Sample of Definitions

- Slight damage
- Medium damage
- Severe damage
- Intermittent failure
- Local failure
- General failure
- Tight closure
- Blow out
- Incipient swelling
- Incipient damage
- Dislodge of rock section
- Large displacement
- Minor damage
- Damage!

Damage by Earthquakes



Slot wall: PPV = 0.75-1.5 m/s

Calculated PPV and associated damage to underground excavations by earthquakes, Brady, 1991

Damage of Swedish Hard Rock (Persson, 1997)

Peak Particle Velocity (mm/s)	Tensile Stress (Mpa)	Strain Energy (J/kg)	Typical effect
700	8.7	0.25	Incipient swelling
1000	12.5	0.5	Incipient damage
2500	31.2	3.1	Fragmentation
5000	62.4	12.5	Good fragmentation
15,000	187	112.5	crushing

Tunnel Damage (Li & Huang,1994)

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Rock	Rock Parameters			Peak Particle Velocity, mm/s			
Type	Unit Weight (g/cm^3)	Comp. strength (Ppa)	Tensile Strength (MPa)	No Damage	Slight Damage (slight cracking)	Medium Damage (partial collapse)	Serious Damage (large collapse)
Hard	2.6-2.7	75-110	2.1-3.4	270	540	820	1530
Rock	2.7-2.9	110-180	3.4-5.1	310	620	960	1780
	2.7.-2.9	180-200	5.1-5.7	360	720	1110	2090
Soft	2.0-2.5	40-100	1.1-3.1	290	580	900	1670
Rock	2.0-2.5	100-160	3.4-4.5	350	700	1070	1990

1-D Elastic Calculations (Zukas, 1982)

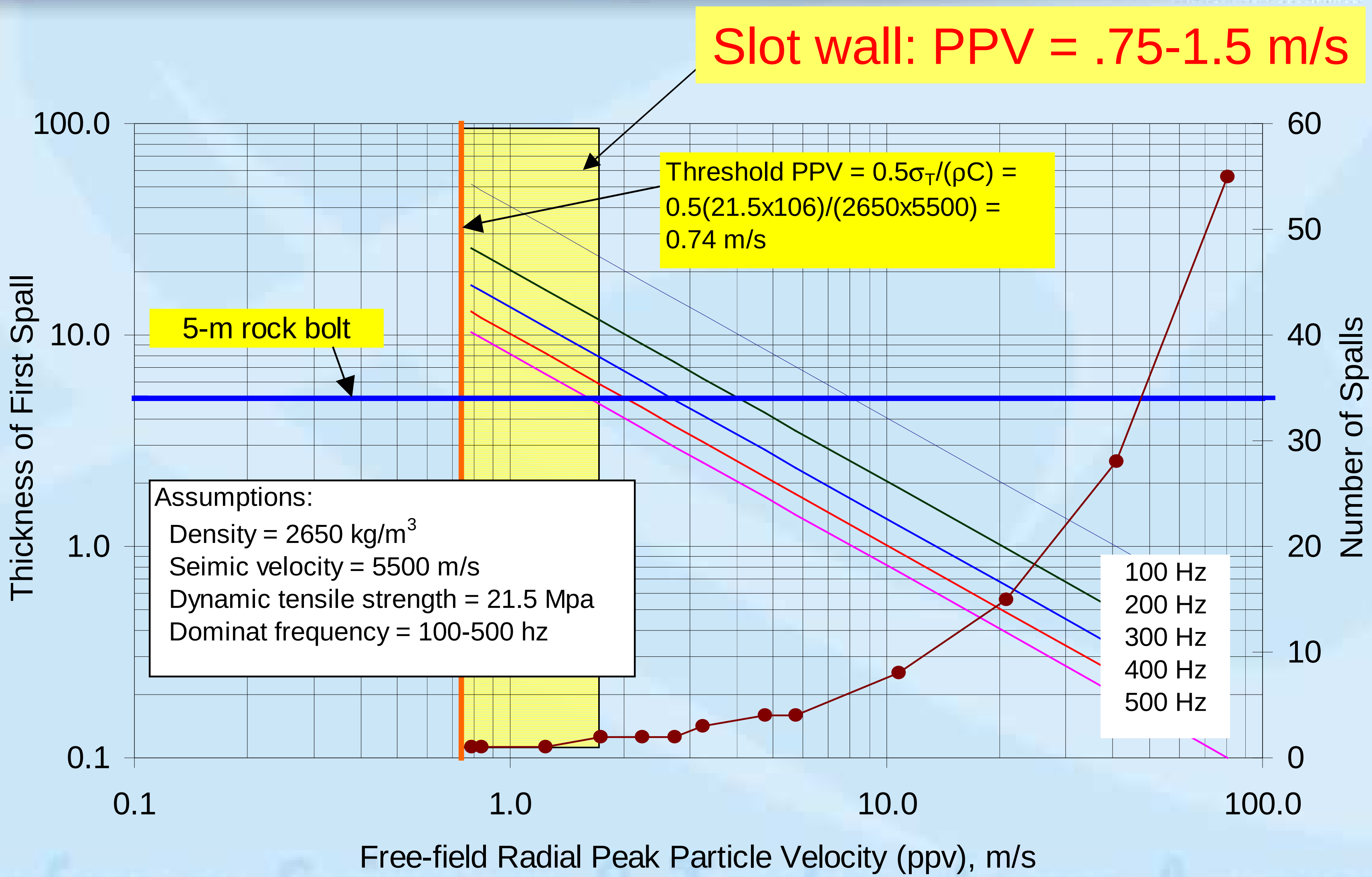
- A saw-tooth wave pulse travelling along a rock bar

$$V_{SP} = \frac{2\sigma_m - \sigma_{DT}}{\rho C} = 2\,ppv - \frac{\sigma_{DT}}{\rho C}$$

$$\sigma_m = ppv(\rho C)$$

V_{SP} = velocity of the first spall; s_{m} = magnitude of incipient stress; σ_{DT} = dynamic tensile strength of rock; ρ = rock mass density, kg/m^3; C = seismic wave velocity in rock, m/s.

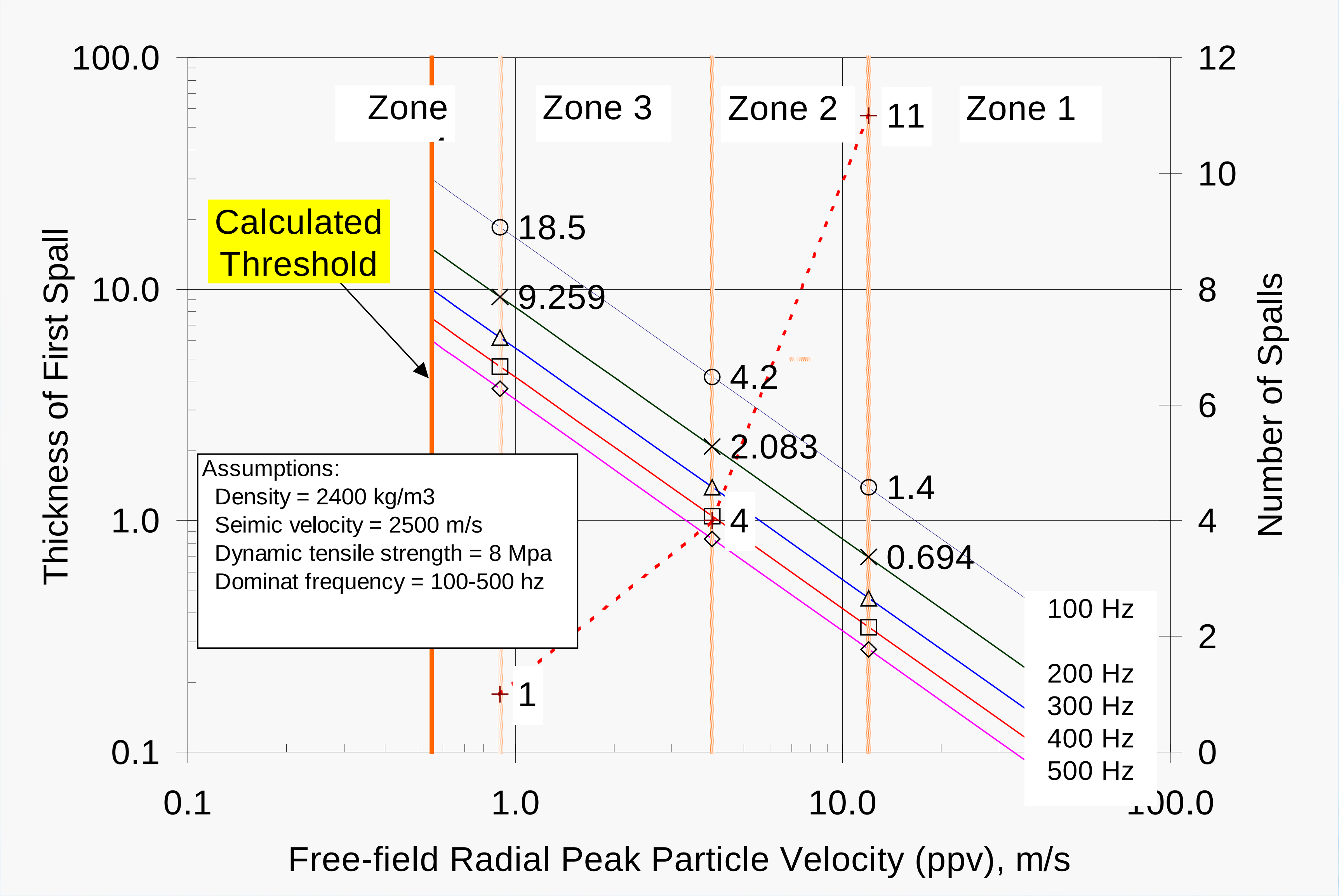
1-D Spall Calculations



UET Tests, Sandstone (after Hendron, 1977)

Damage Zone	1	2	3	4
Damage	tight closure	General failure	Local failure	Intermittent failure
Free-field radial strain	NA	40	13	3-6
Free-field ppv, m/s	NA	12	4	0.9-1.8
Calculated thickness of 1st spall, m		0.3-1.4	1-4.2	2-18.5
Calculated number of spalls		11	4	1

1-D Spall Calculation for UET



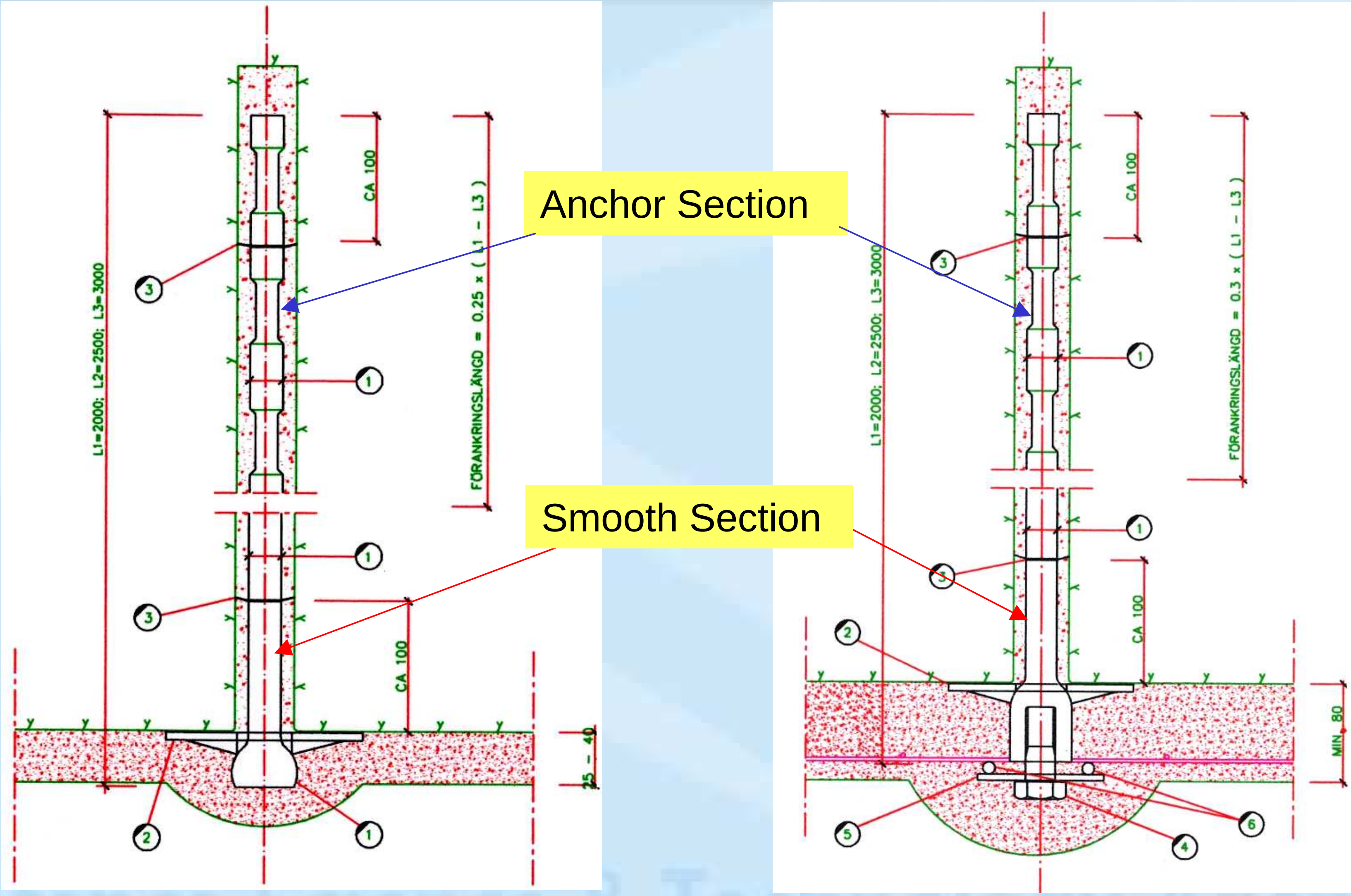
Explosive Testing of Tunnel Response (Dowding, 1984)

Type	Strain%	PPV, m/s
Unlined tunnel:		
Joint movement, fall of loose rock		0.3
Intermittent failure	0.015	2.0
Local failure	0.04	3.6
Complete closure	0.1	
Lined tunnel:		
Cracking of liner	0.02	1.0
Displacement of cracks		1.3
Local failure	0.15	7.4
Complete failure	0.8	40.0

Design of Tunnel Support

- Unlined tunnel can sustain ground shock of PPV = 1.0-2.0 mm/s before damage begins
- Static support design specified fibre-reinforced shotcrete and rock bolts for increased performance against dynamic loads
- *Swedish Armed Forces HQ Requirements: all military facilities in rock must use dynamic rock bolts*

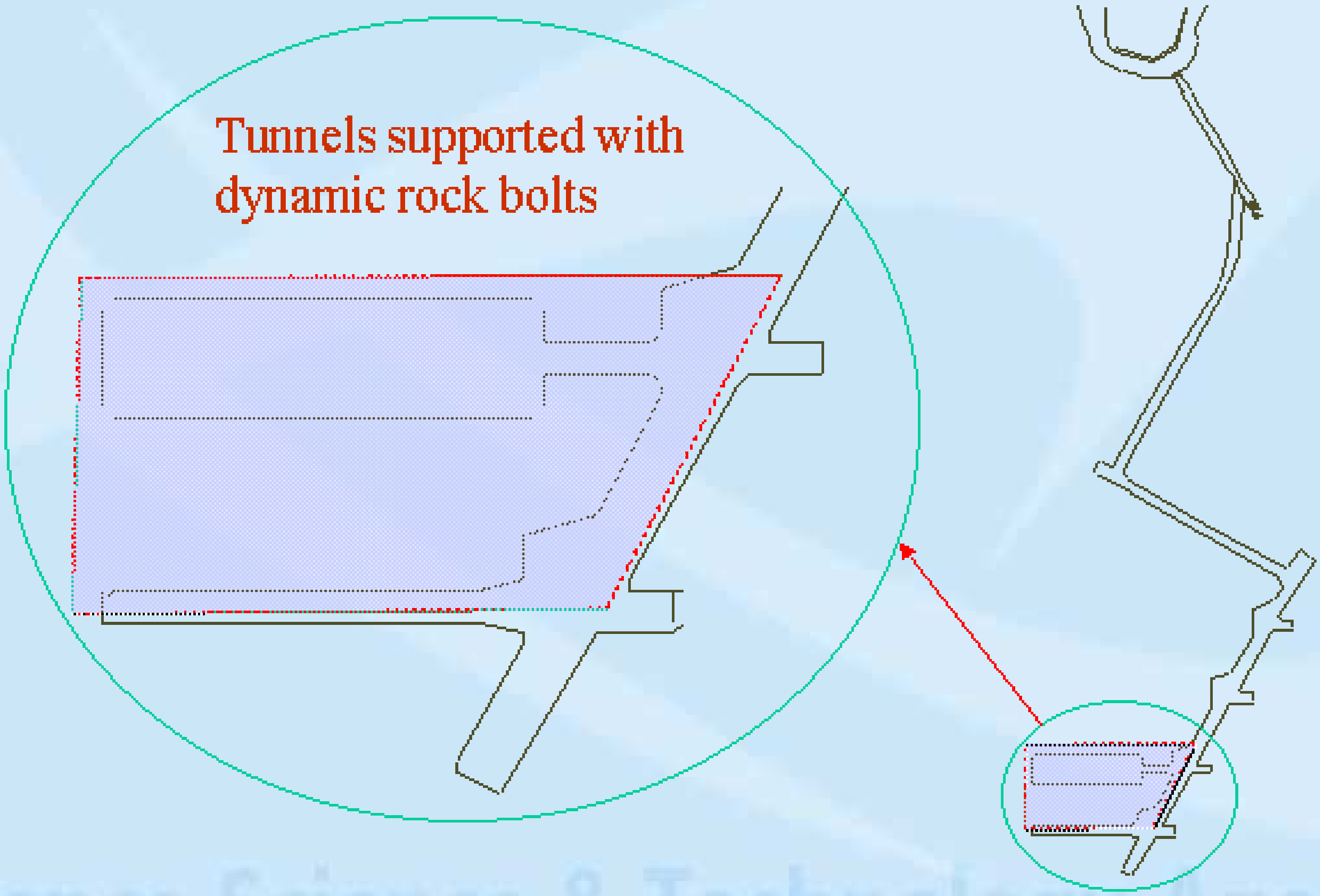
Swedish Dynamic Rock Bolts



Plain shotcrete

Reinforced shotcrete

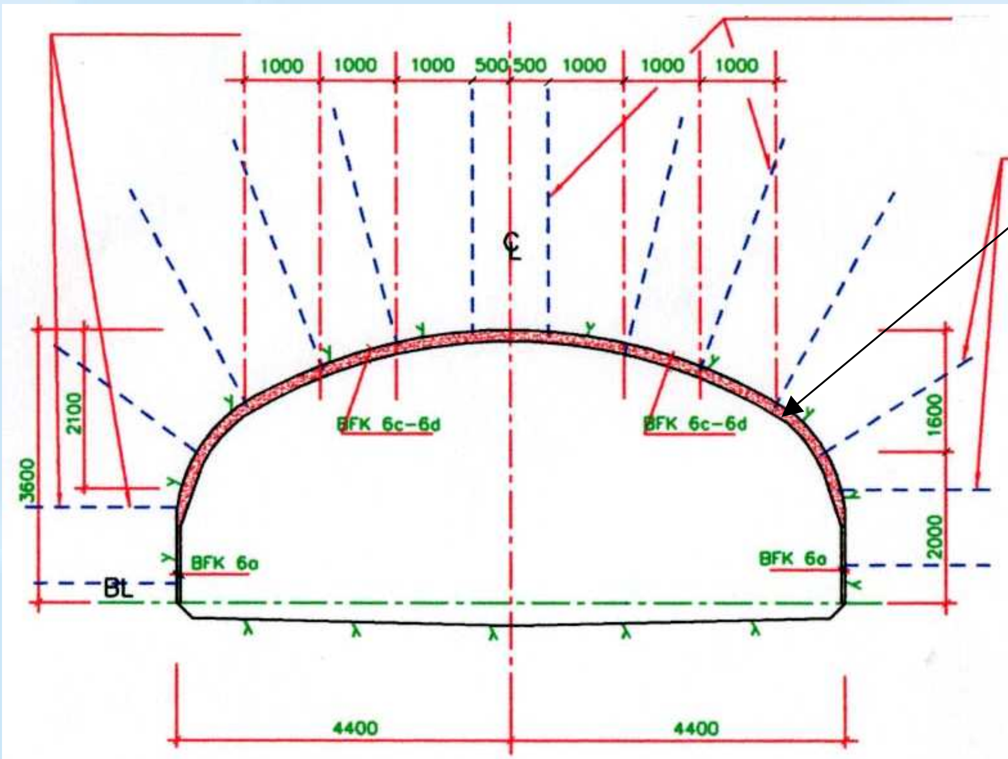
Tunnel Support for LST



Tunnel Support for LST

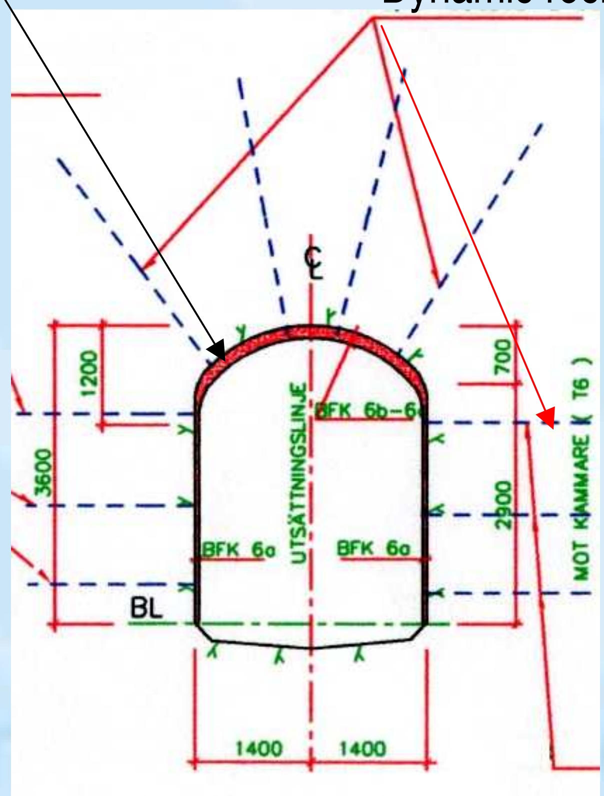
Dynamic rock bolts

SFR Shotcrete



Chamber

Dynamic rock bolts

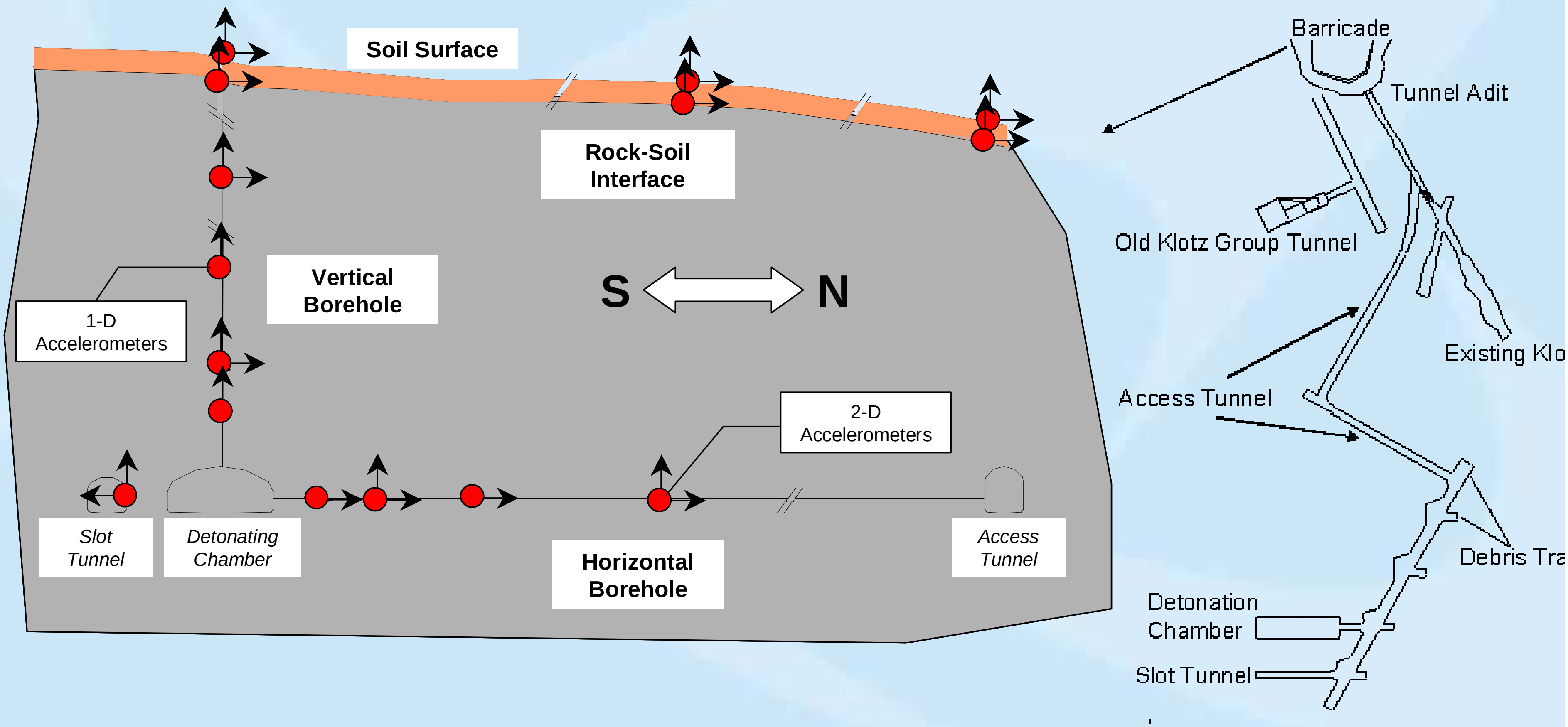


Slot Tunnel

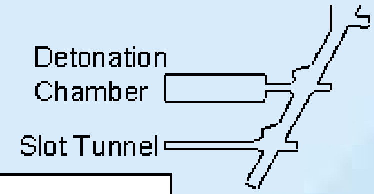
LST - Instrumentation

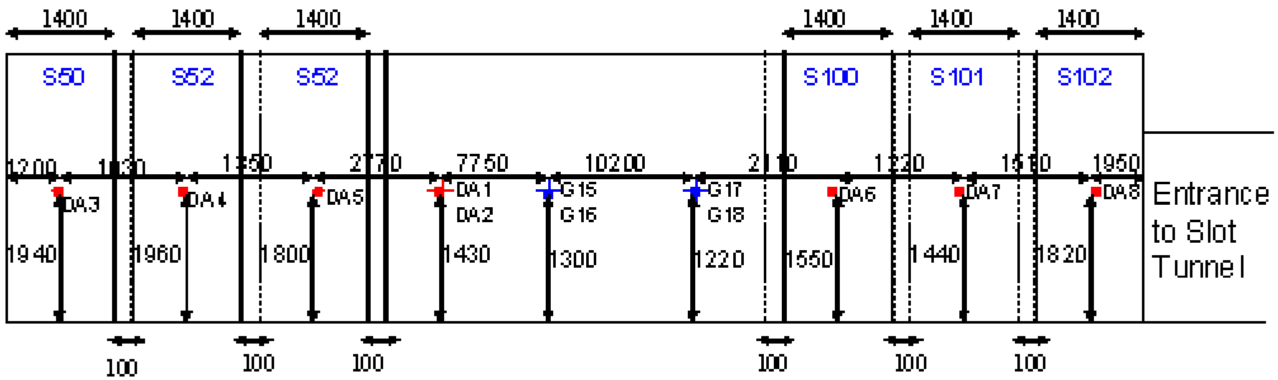
Organisation	Gauge Type	2000	2001	Remarks
FOI	Air Blast – Chamber	3	3	
	Airblast – Tunnel	21	21	
	Airblast – External	8	8	
	Ground Shock	40	40	
	Strain	8	8	
	Temperature	1	12	New - 11
	Smoke puffs	0	0	Consider for future tests
NDCS	Air Blast	11	11	
	Ground Shock	16	16	
	Airblast Induced Ground shock	0	2	New
	Geophones	8	8	
DTRA	Chamber – Pressure	2	2	
	Chamber – Bargauge	2	2	
	Pressure – External	4	8	Stings (4)
	Accelerometer	8	12	
	Radar – Fragment Vel.	1	2	
	Time of Arrival	0	15	New
		133	**170**	

Ground Shock Gauges



Shotcrete Pannels in Slot Tunnel



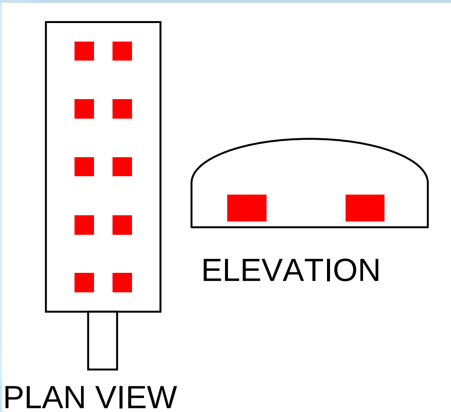


Panel Number	Gauge Number	Panel Thickness (mm)	Fibre Density (kg/m3)
S50	DA3	50	0
S51	DA4	50	30
S52	DA5	50	60
S100	DA6	100	60
S101	DA7	100	30
S102	DA8	100	0

KEY

- Uniaxial Acc. – DTRA
- Biaxial Acc. – FOA
- Biaxial Acc. – DTRA

TNT Bare Charge (Test #3)



TEST NO.	NEQ (KG)	CHARGE TYPE	OBJECTIVES/ DESCRIPTION
1	10	Bare charge	Ground shock calibration
2	500	Bare charge	Loading density 0.5 kg/m^3
3	10000	Bare charge	Loading density 10 kg/m^3
4a	2500	Bare Charge	Loading density 2.5 kg/m^3
4b	10000	Cased Charge	Cased charge Test Loading density 10 kg/m^3

Vide of Test #3 - 10000 Kg TNT

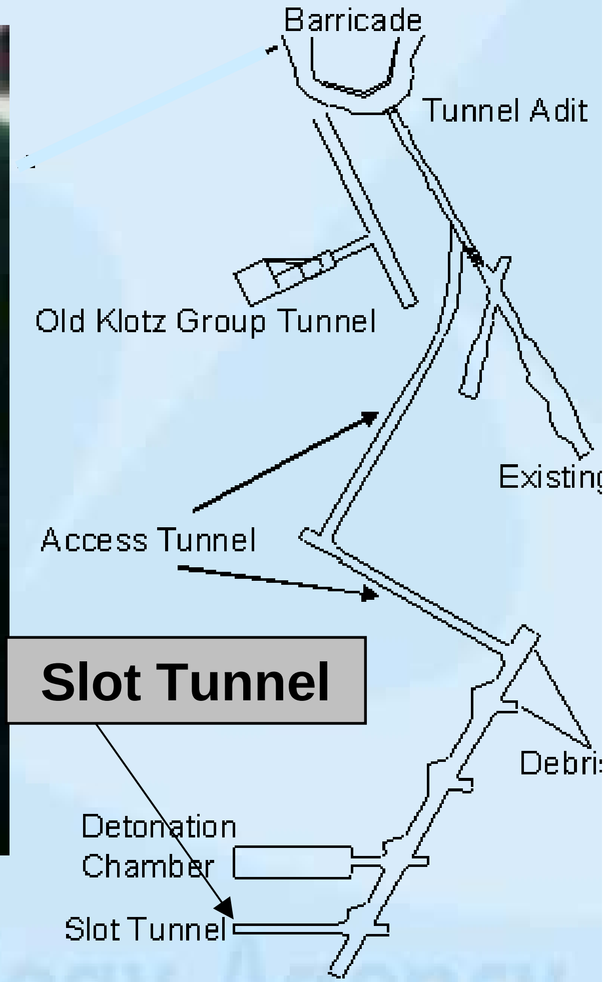
Chamber

- 10 craters in floor underneath charge
- No rock fall from roof!

Overview of Chamber

Crater

Video Of Slot During Test #3



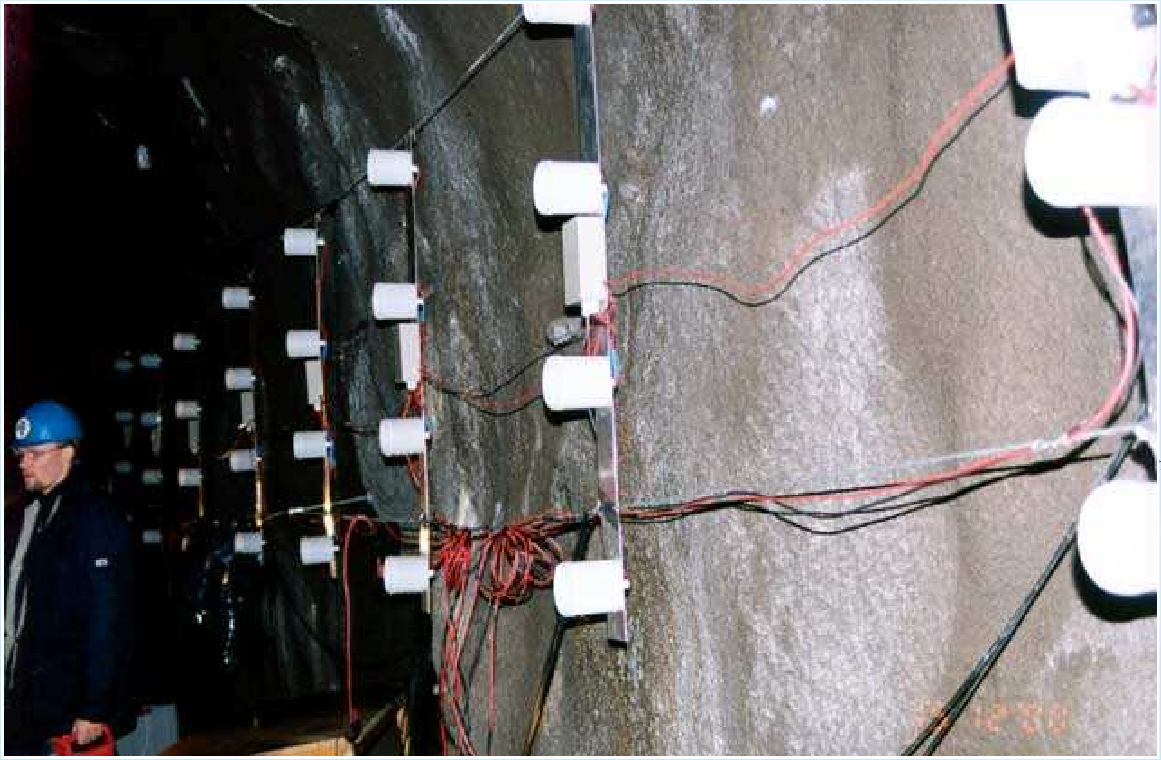
Slot Tunnel

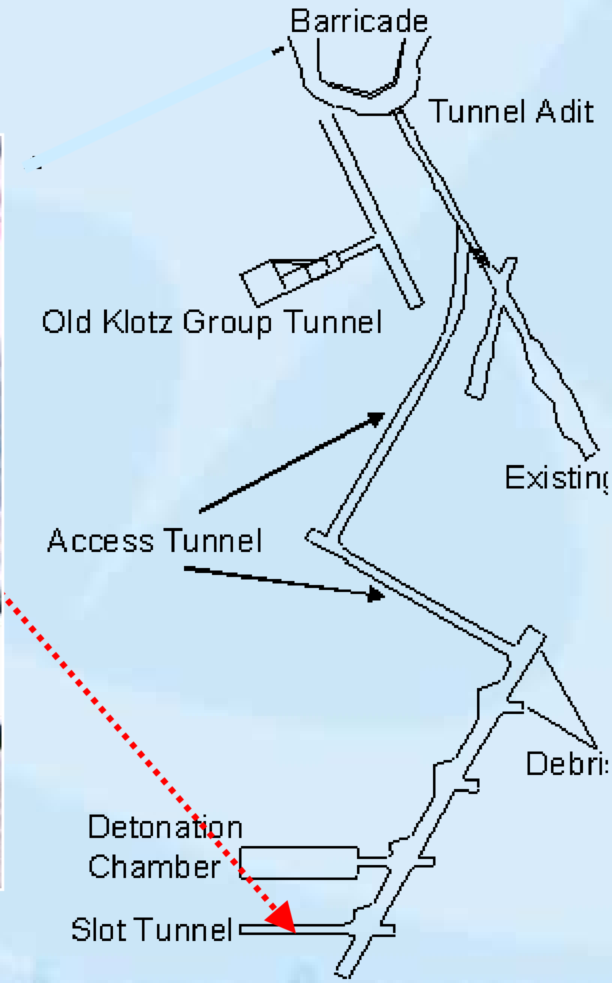
- No visible damage of tunnel wall
- Slight soil movement on floor

Shotcrete Wall

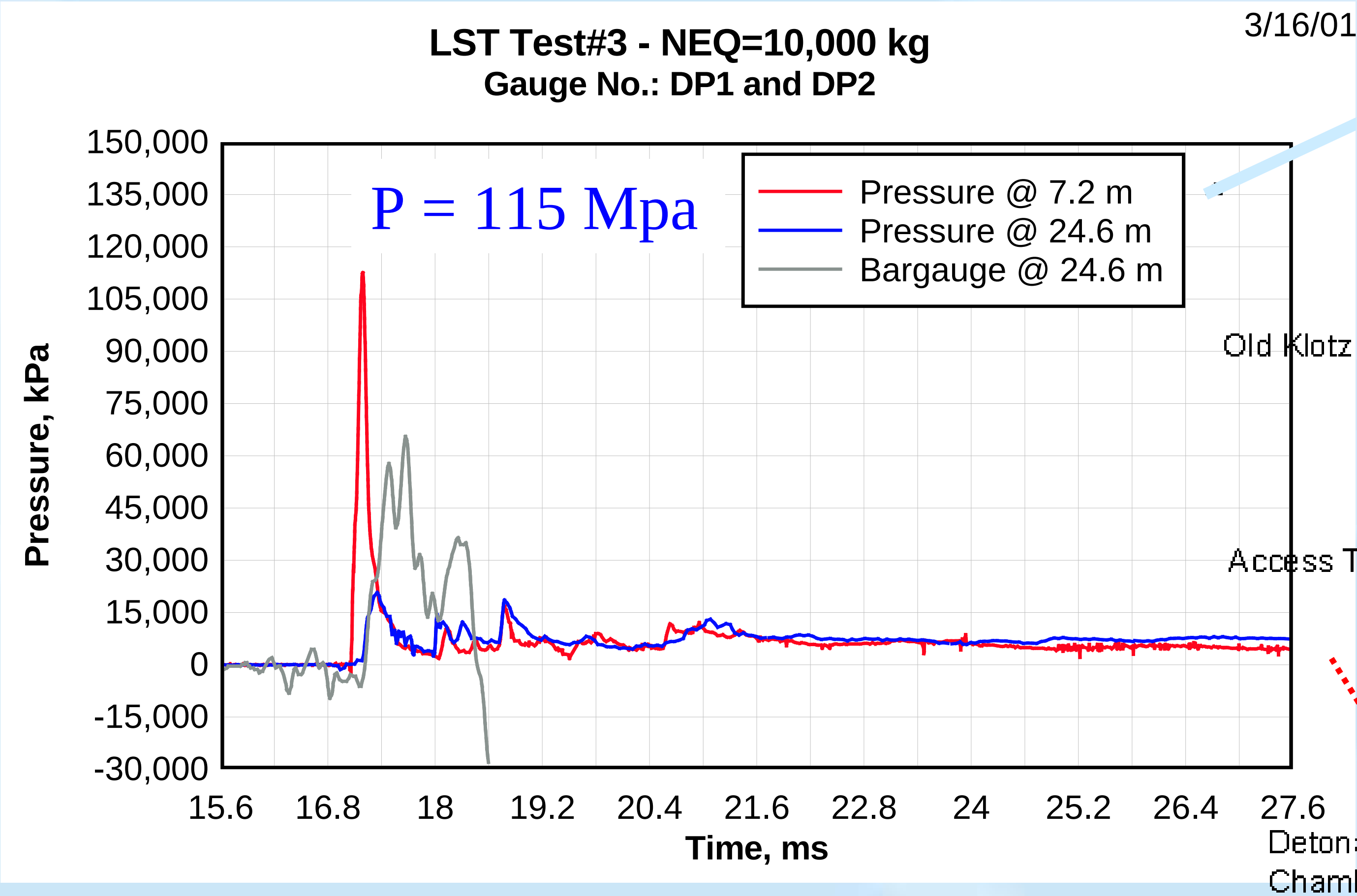
Slot Tunnel

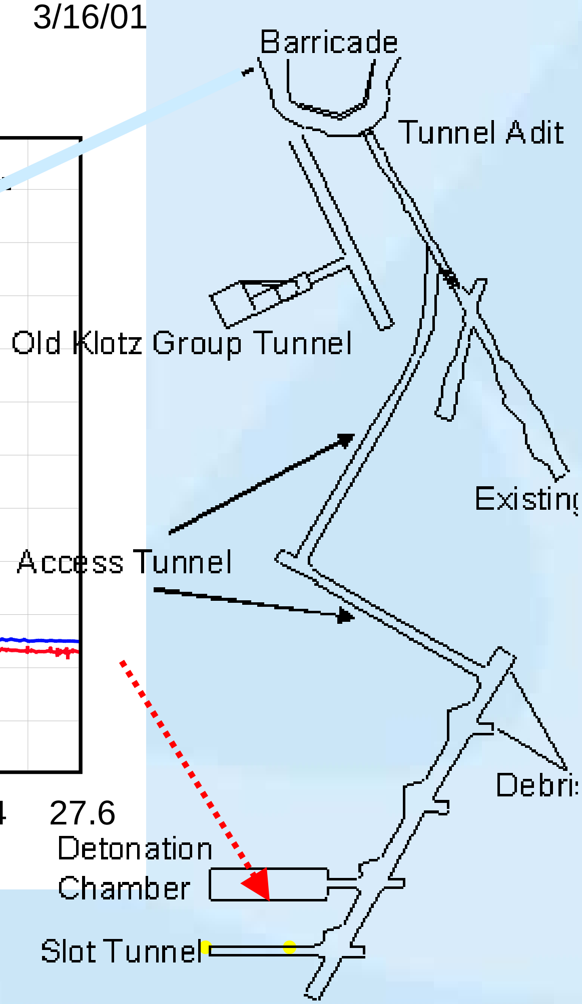
- Lights (and all other fixtures) fully functional after detonation





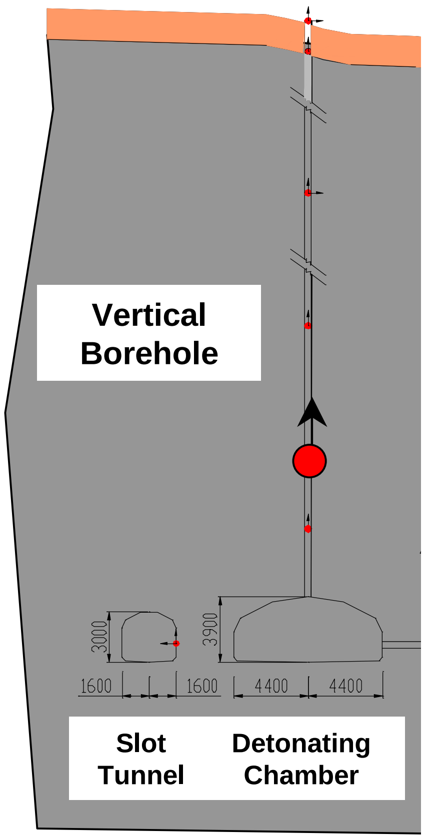
Chamber Pressure

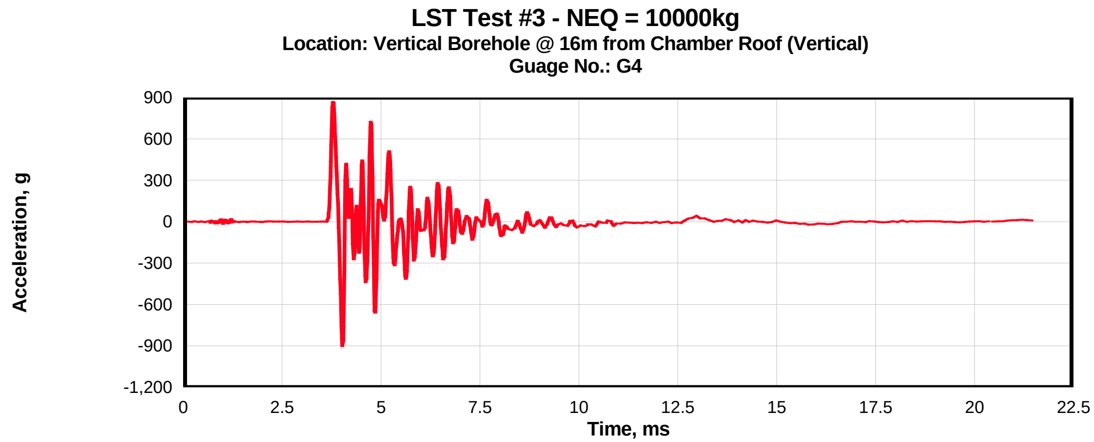


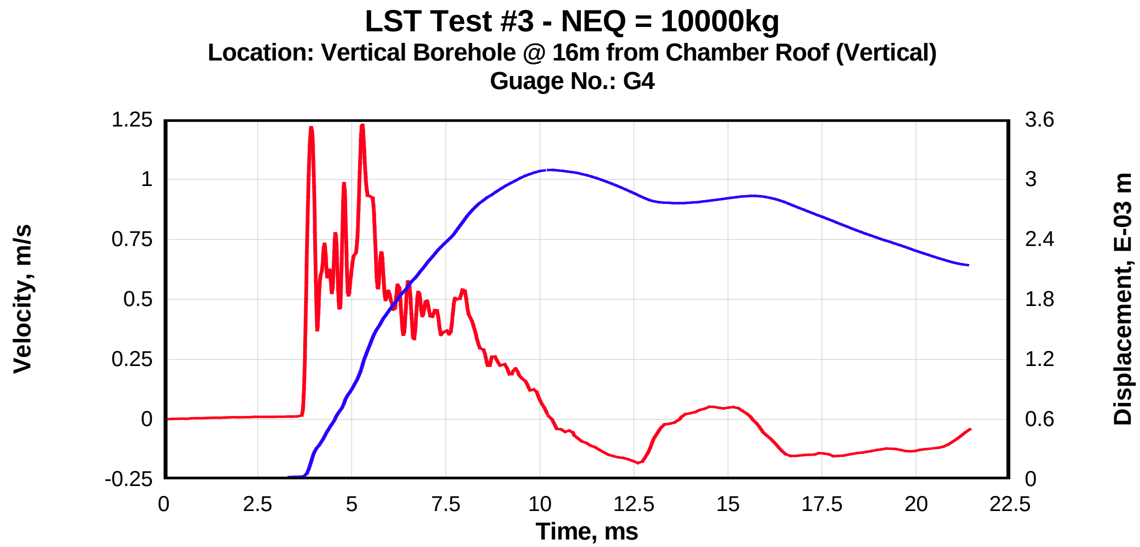


Equivalent PPV = [115 Mpa/(2620x5000)] = 8.8 m/s

VERTICAL BOREHOLE







HORIZONTAL BOREHOLE

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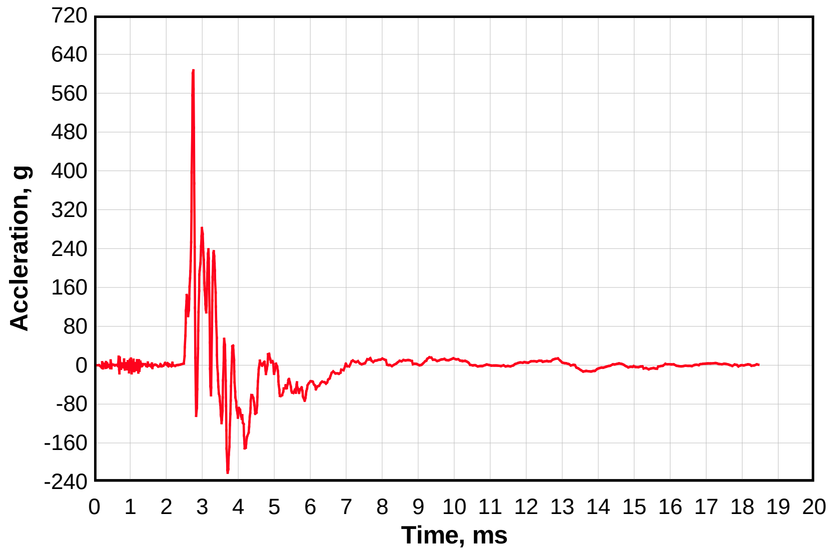
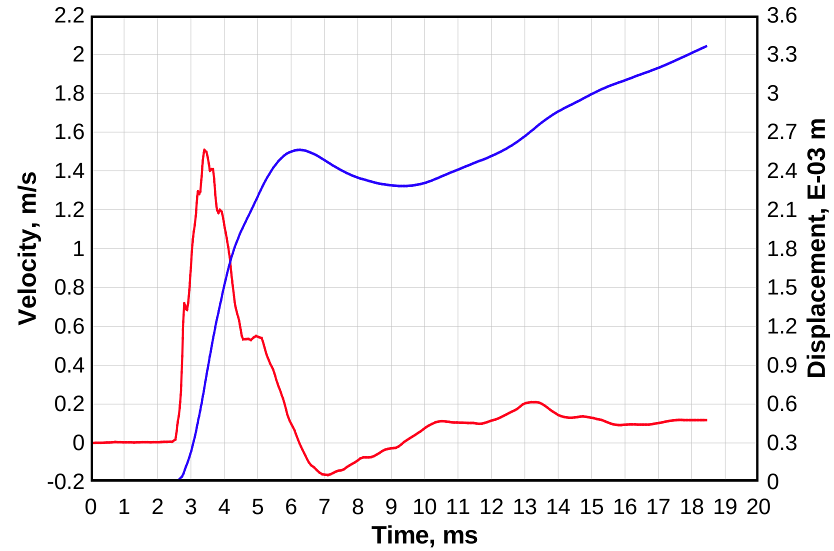
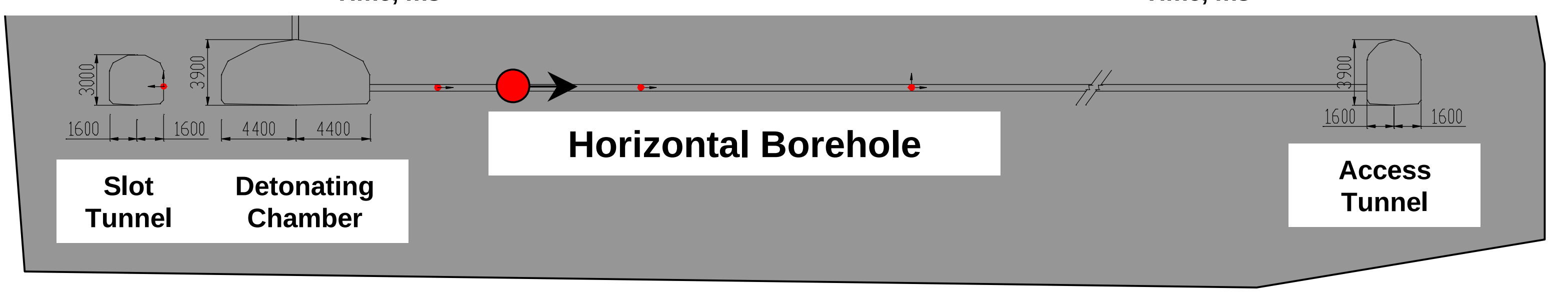
LST Test #3 - NEQ = 10000kg
Location: Horizontal Borehole @ 18m from Chamber Wall (Horizontal)
Guage No.: G10



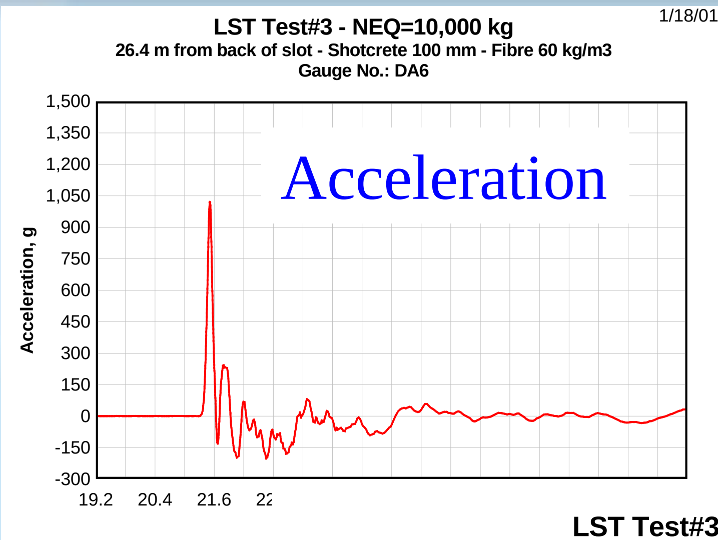
3/16/01

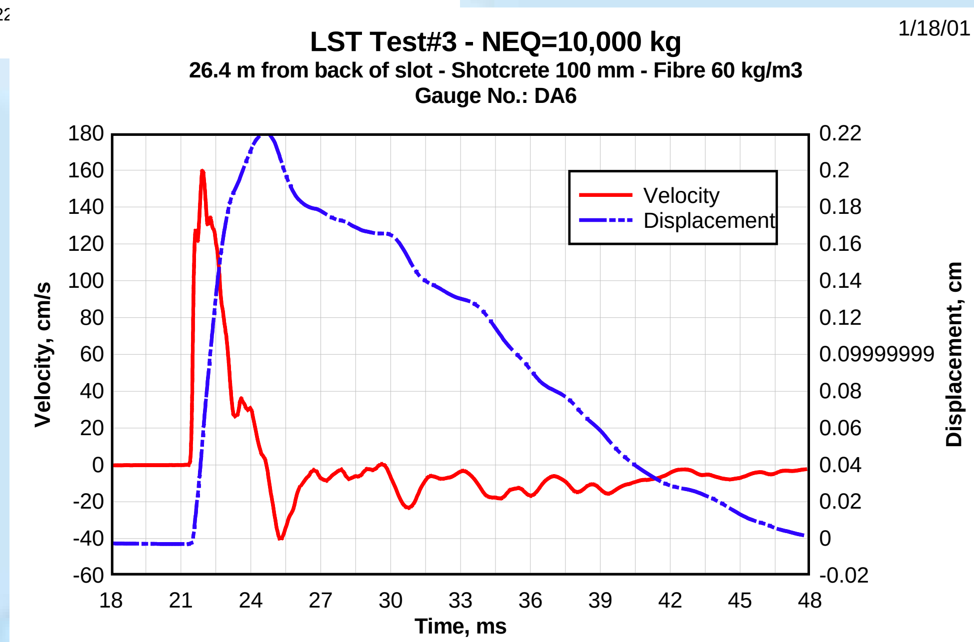
LST Test #3 - NEQ = 10000kg
Location: Horizontal Borehole @ 18m from Chamber Wall (Horizontal)
Guage No.: G10

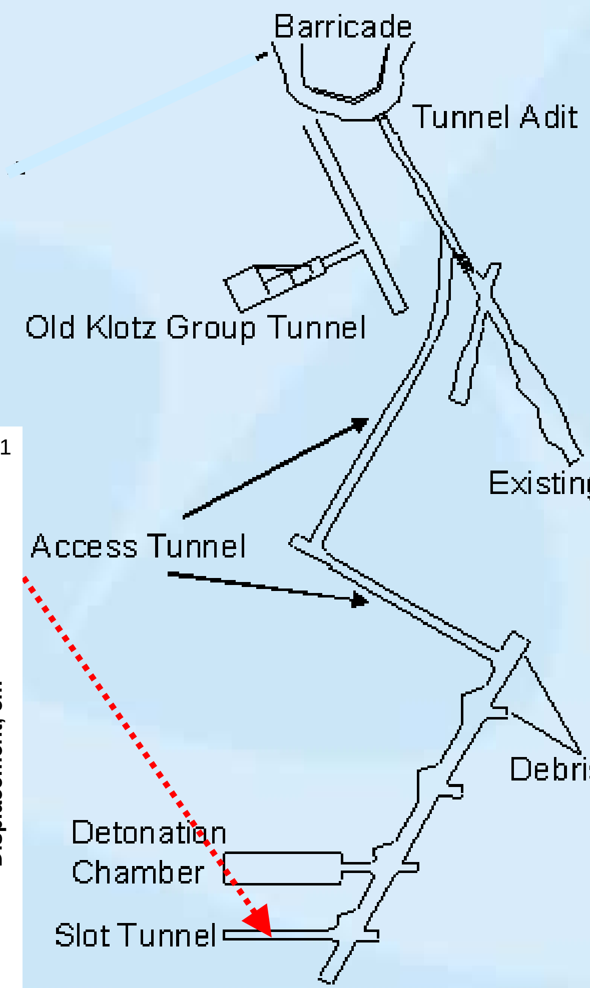




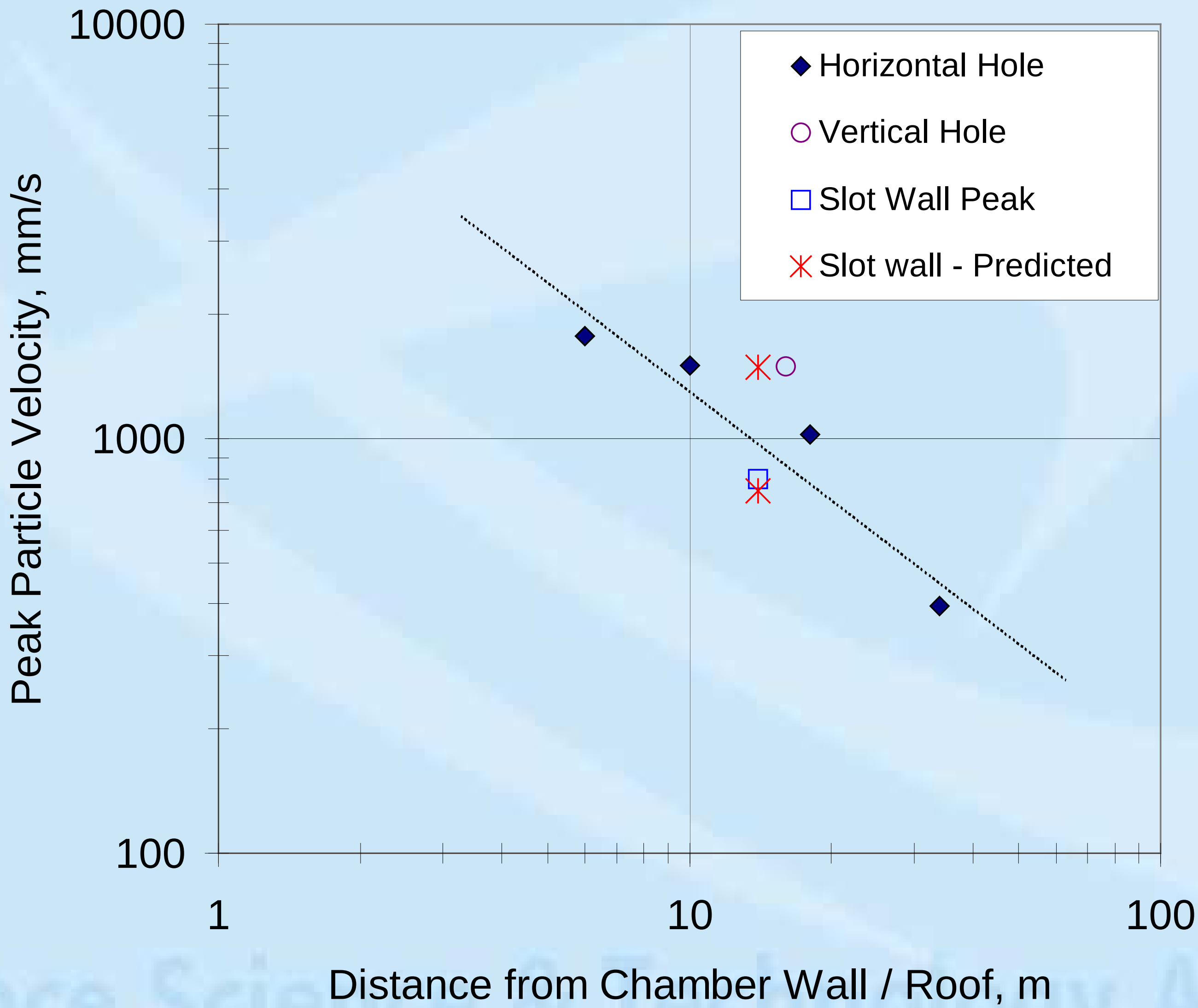
Ground Shock on Slot Walls



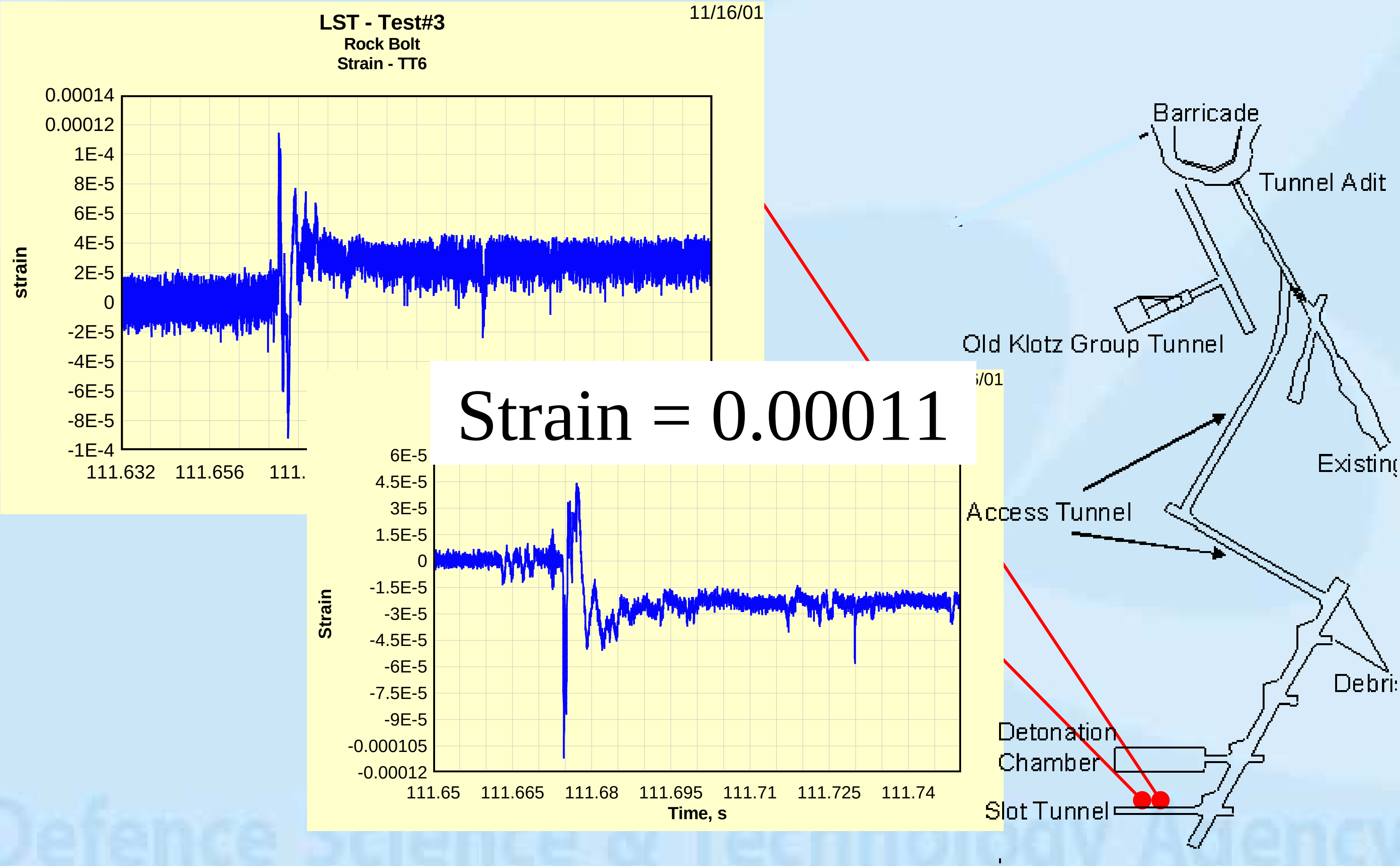




PPV's from Test #3

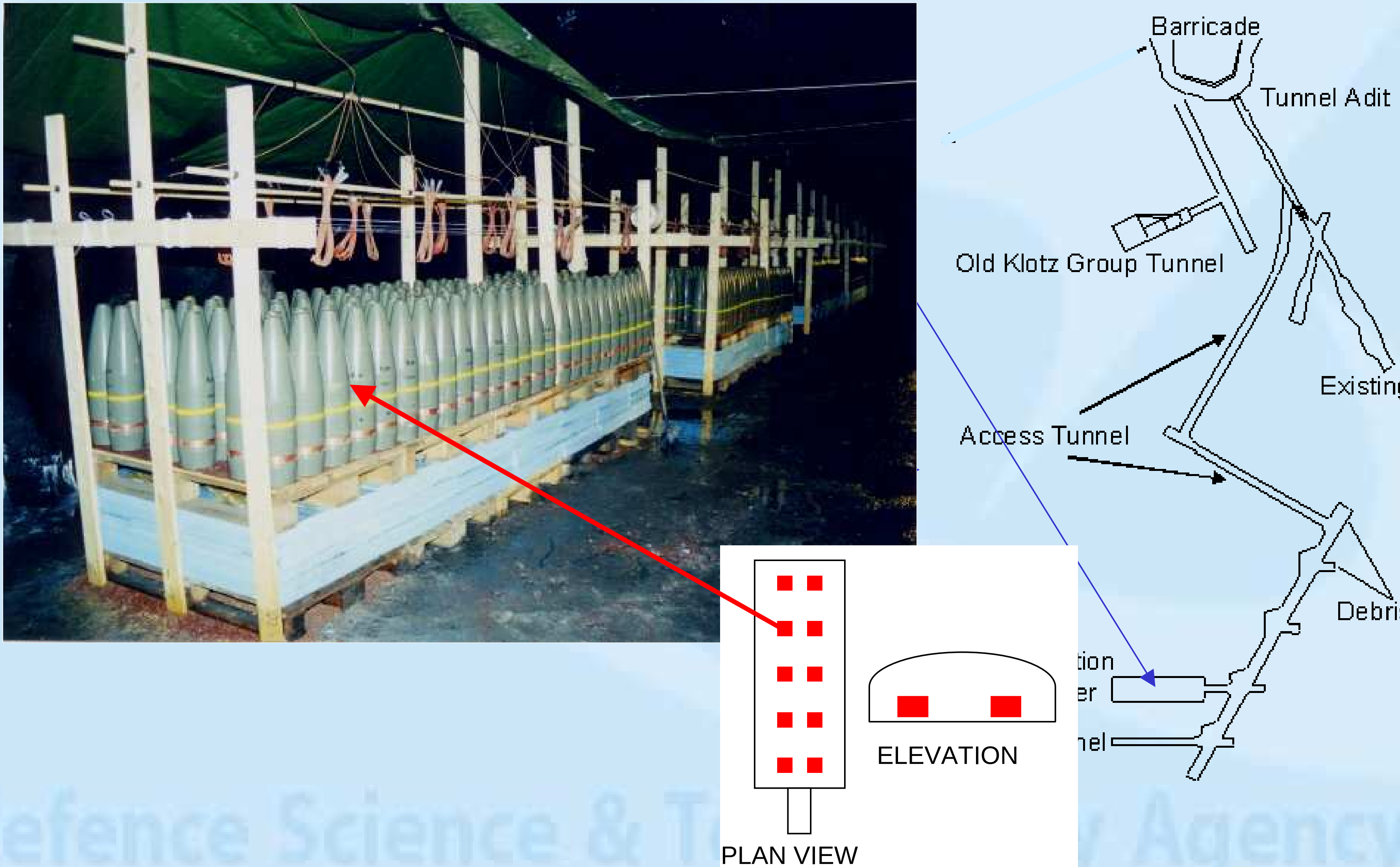


Strain on Rock Bolts (T3)



Strain = 0.00011

Fragment Loading (Test #4b)



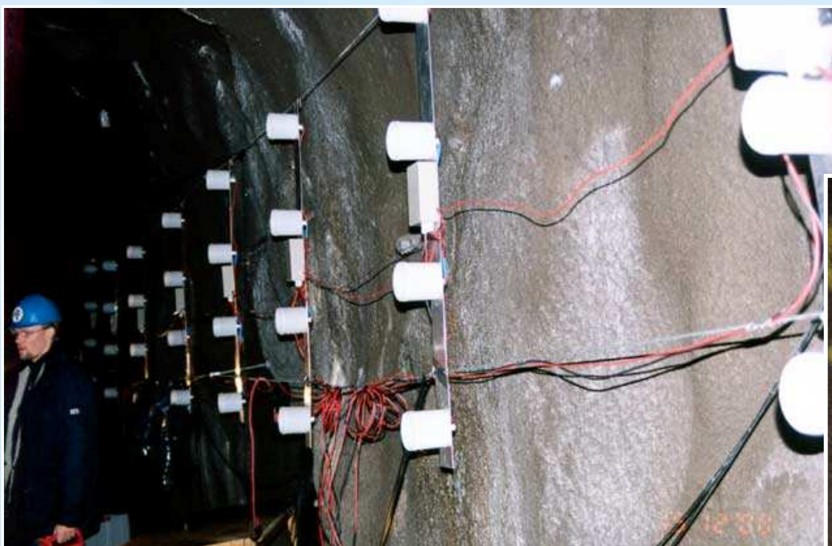
Video of Test #4b

Damage in Chamber

- Spalling of shotcrete layer
- Still no rock fall from roof!

Slot Tunnel

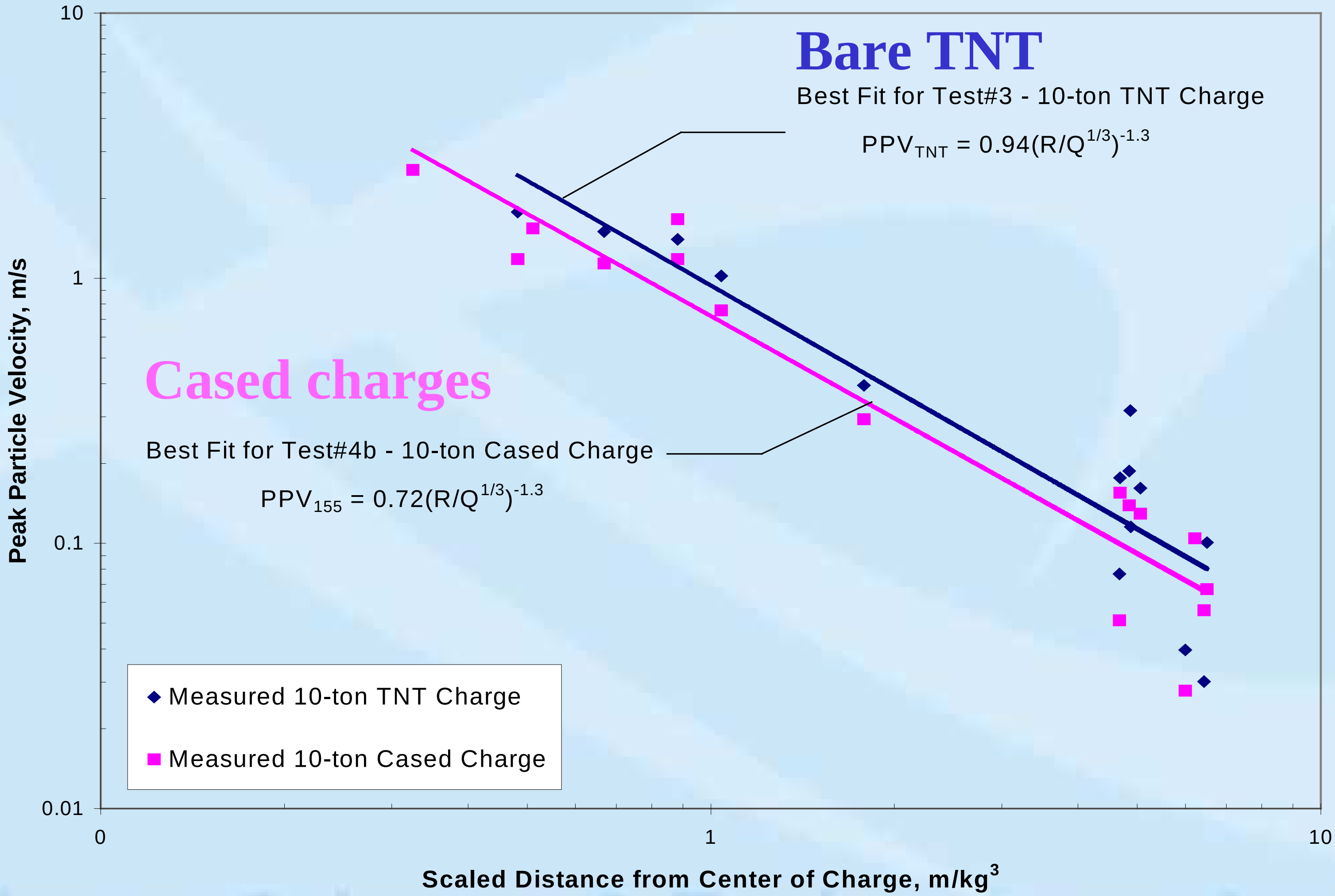
- Lights (and fixtures) still fully functional during and after the test
- Damaged shotcrete fell off to floor



Light Fixtures

Shotcrete Panels

Comparison of PPV's



Effects of Fragment Loading

Items	Test #3	Test #4b
Min PPV, m/s	0.94	0.62
Ratio of Min PPV	1.00	0.66
Max PPV, m/s	1.70	1.84
Ratio of Max PPV	1.00	1.09
Average PPV, m/s	1.39	0.98
Ratio of Avg PPV	1.00	0.70
Equivalent TNT Ratio	1.00	0.54

Mostly fragments from outer row of rounds were loading the tunnel walls

Computed Seismic Velocity

Test and Charge	Peak Chamber Pressure, MPa	Average PPV on Tunnel Wall, mm/s	Time of Arrival, Ms	Calculated Seismic Velocity, m/s
Test 1 – 10 ton bare TNT	100	1390	3.07	4,636
Test 2 – 2.5 ton bare TNT		622	3.26	4,268
Test 3 – 10 ton TNT (1450 155mm shells)	50	977	3.28	4,294
Ratio of Seismic Velocity after Test 2			---	0.93

Conclusions

- Fresh rock damage appears to begin at PPV's of 1-2 m/s
- At incipient PPV's of 2-4 m/s, static support with rock bolts and fibre-reinforced shotcrete sufficient for tunnels in competent rock
- For low loading densities (10 kg/m^3), tunnels sited at $0.6Q^{1/3}$ in hard rock can remain fully functional against ground shock loading

Finally,

If in doubt . . .

岩

. . . build in rock

THANK YOU

THANK YOU