

The Underground Storage Facility in Singapore

Experience with Norwegian Underground Technology

Presented at Workshop on Norwegian Tunnelling Technology

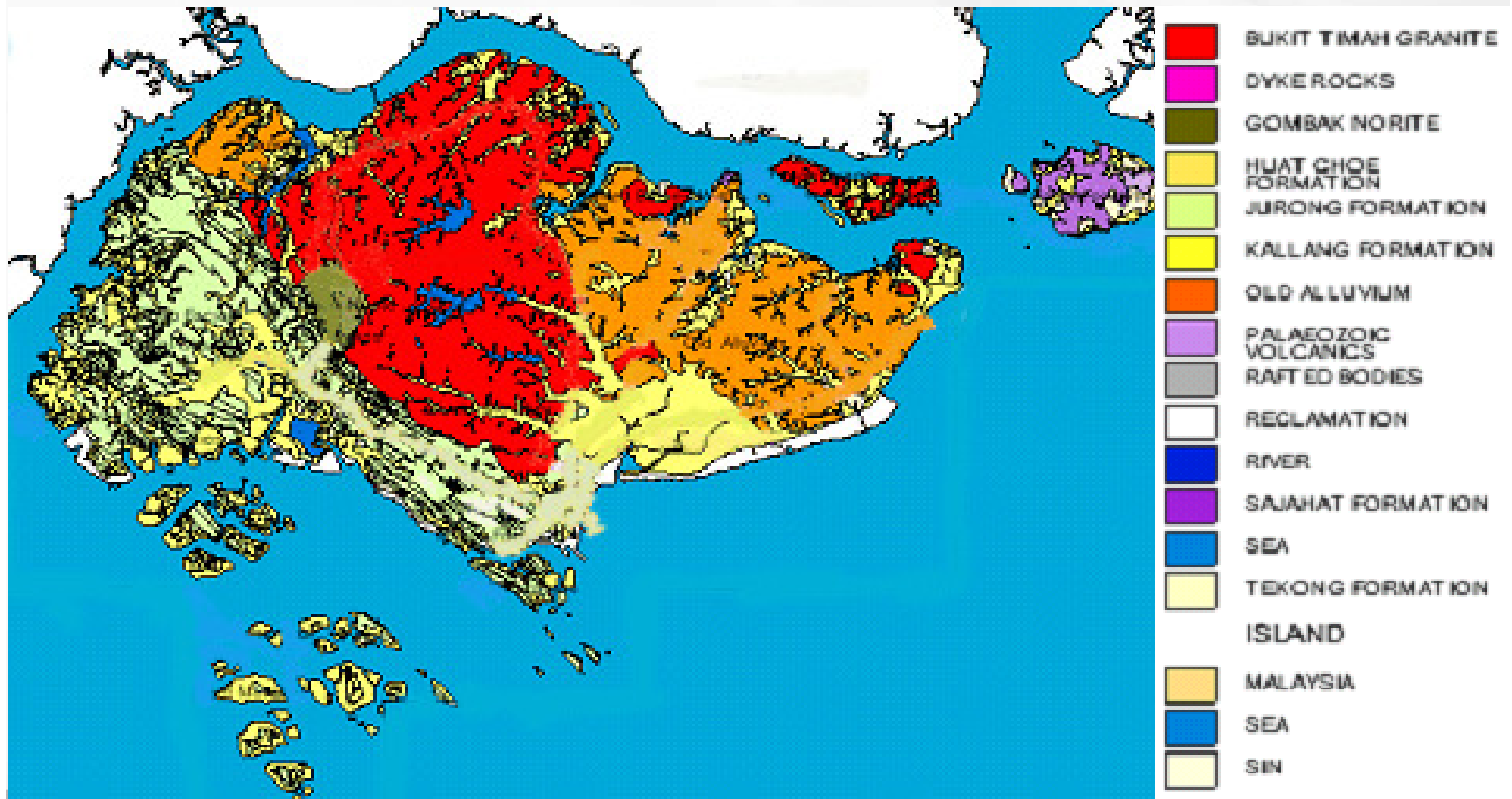
17-18 February 2009

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Programme Manager (Rock Cavern Facilities Development)
Defence Science & Technology Agency

President, Society for Rock Mechanics & Engineering Geology Singapore

PROJECT BACKGROUND

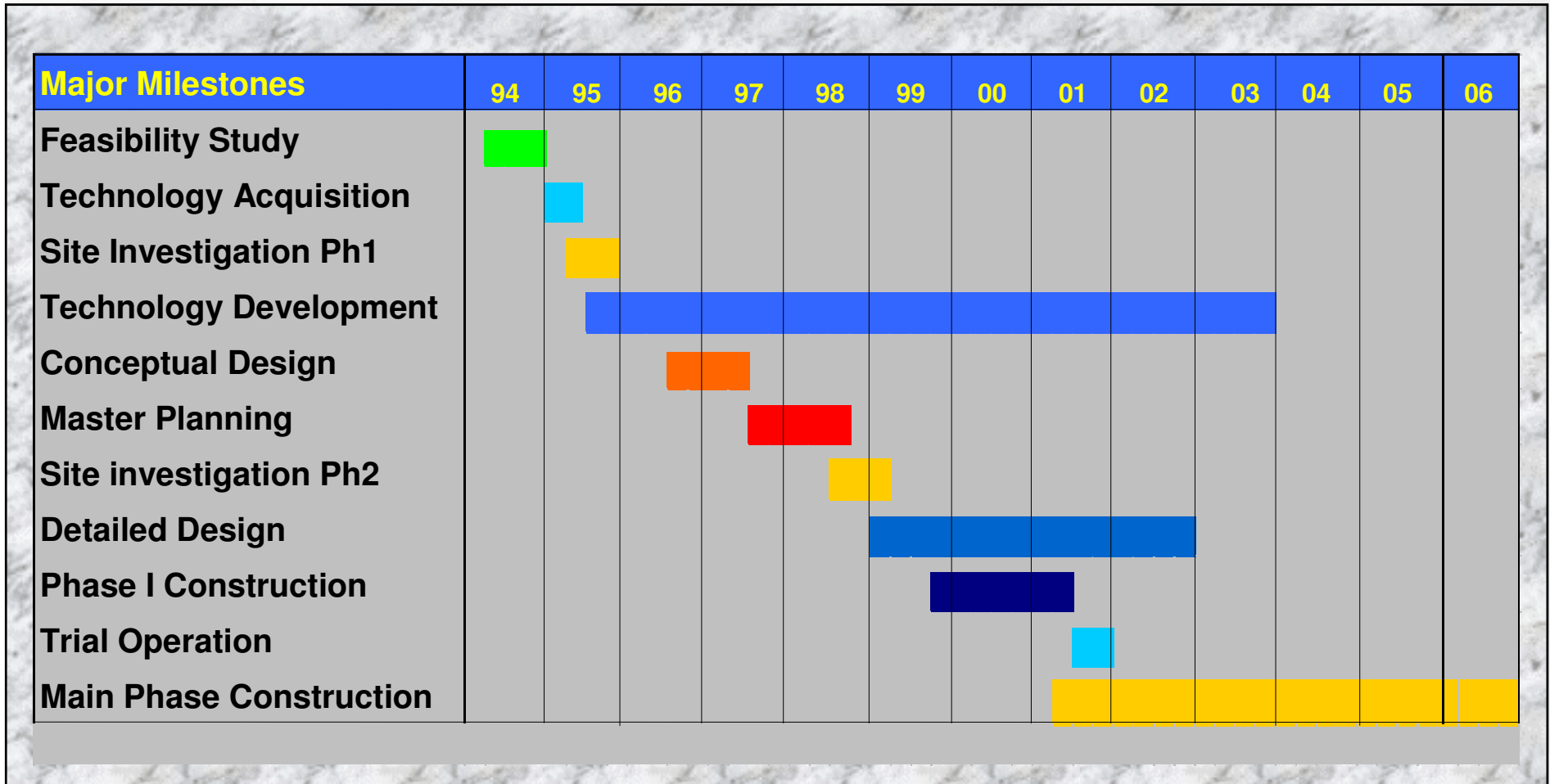
Geology Map of Singapore



View of A Completed Cavern



Major Project Milestones

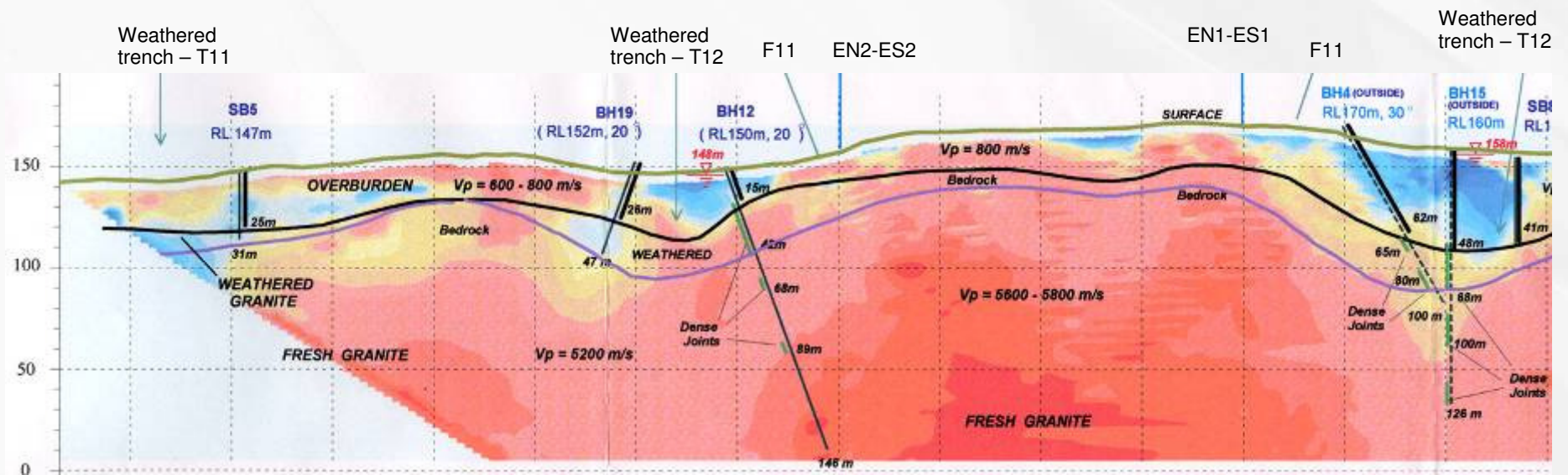


ROCK ENGINEERING

Summary of Main Site Investigations

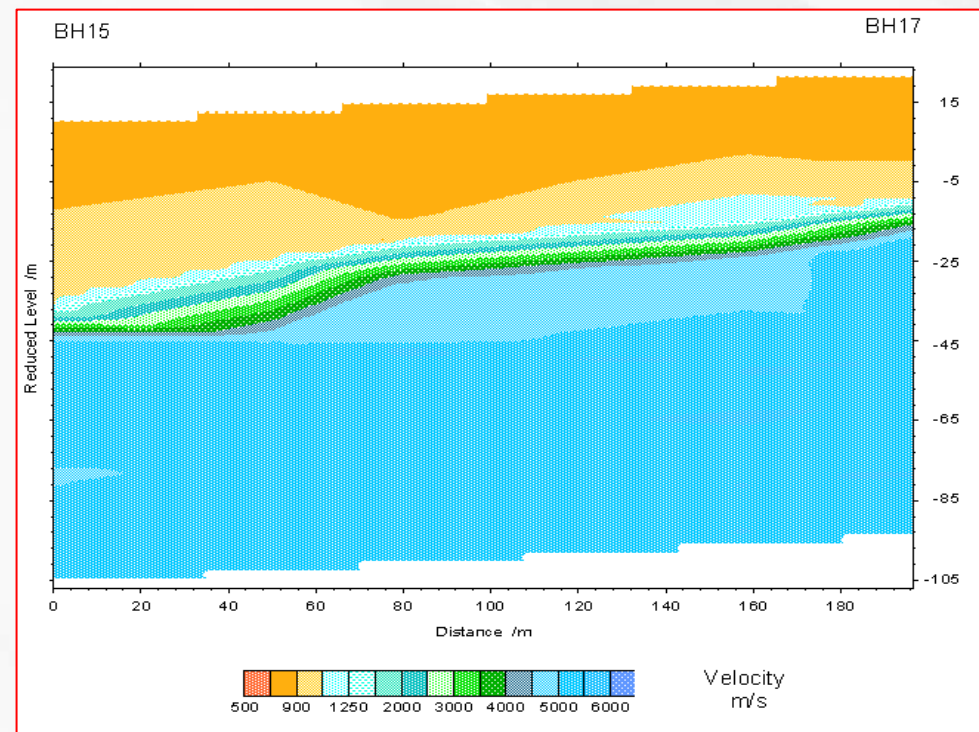
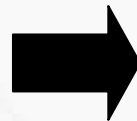
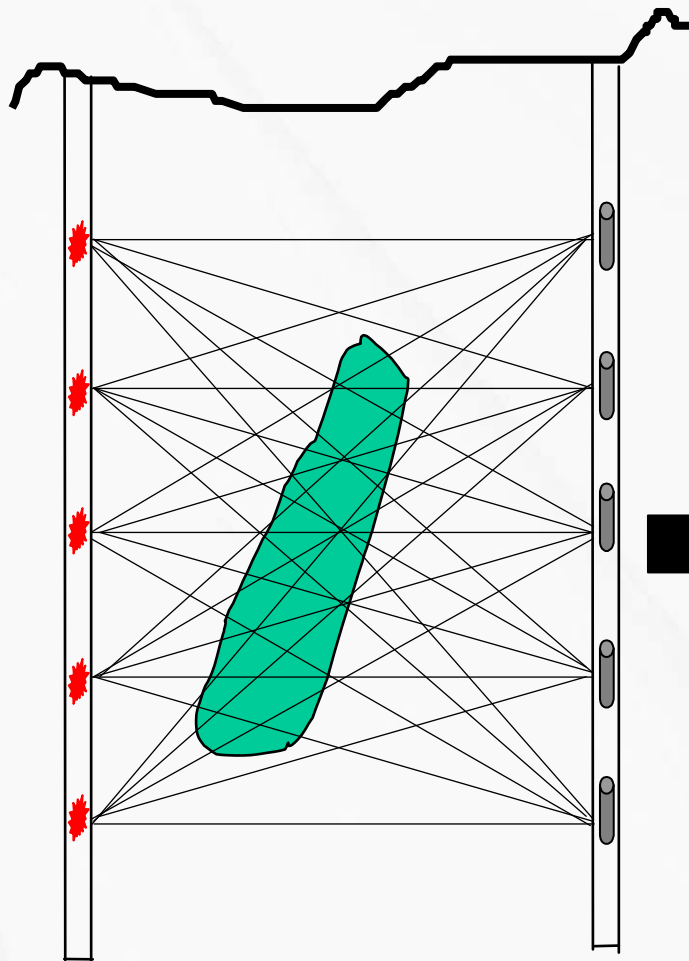
Type	Methods
Drilling	Soil boring; diamond core drilling
Surface geophysical surveys	Seismic refraction/reflection; electric resistivity tomography
Borehole surveys and testing	Borehole logging; seismic logging; borehole camera acoustic imaging; impression packer; borehole radar; Lugeon tests; rising head/falling head tests; cross-hole tomography
Laboratory tests	Point load; uniaxial/triaxial compression; Brazil tensile; 3-point flexural
<i>In situ</i> stress	Hydraulic fracturing; 3-D overcoring

Composite Geological Profile

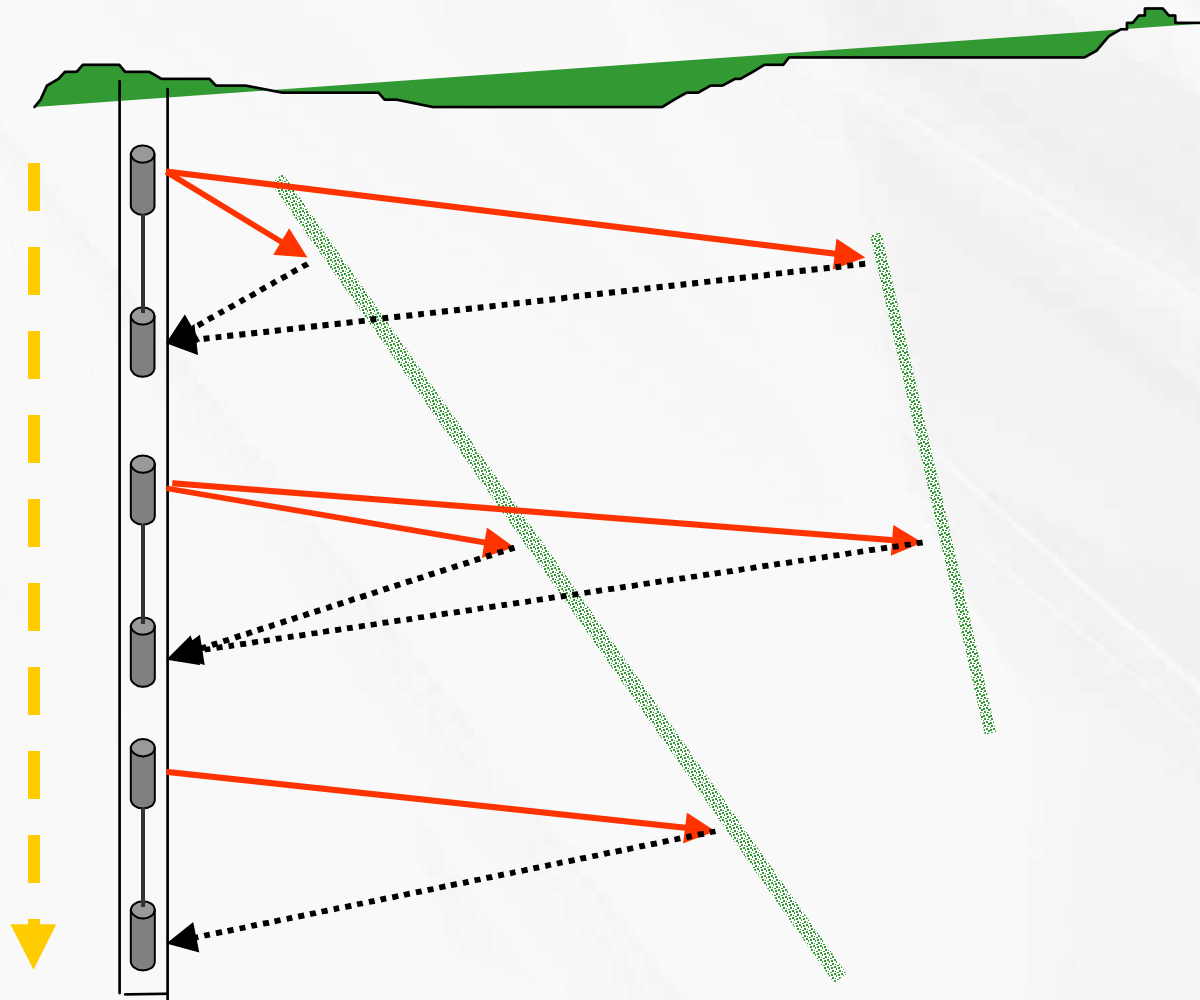


- Joint imaging using electrical resistivity and seismic refraction surveys

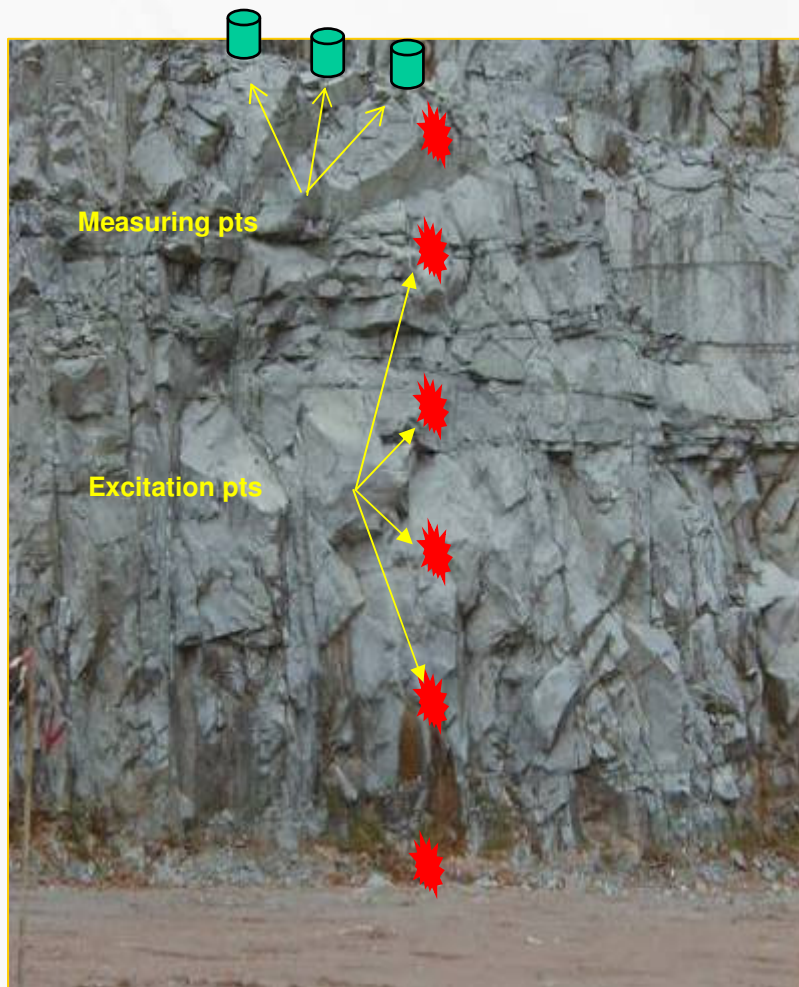
Cross-hole Tomography



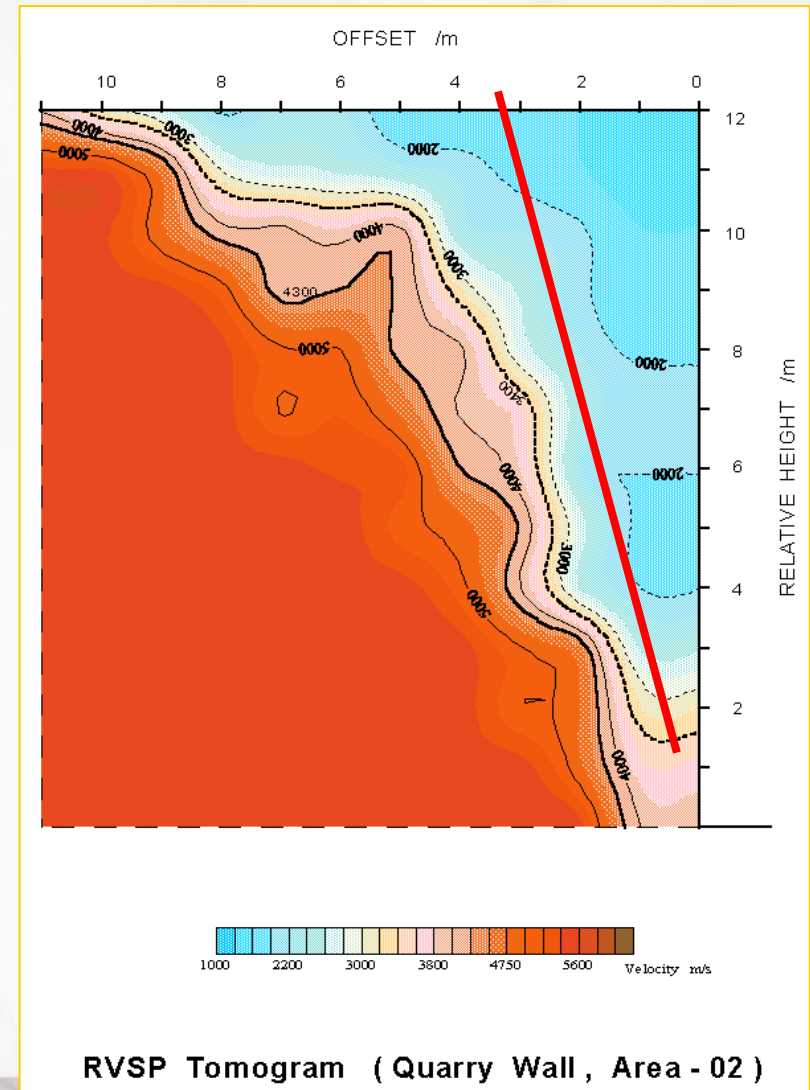
Borehole Radar Image



Vertical Seismic Profiling



Determining stability of quarry wall

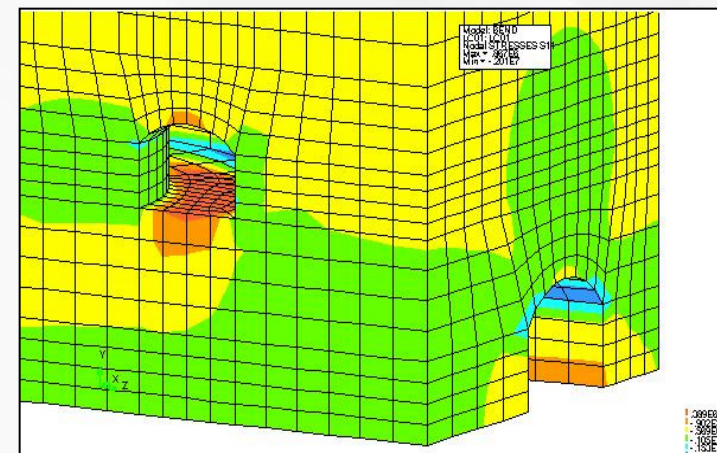
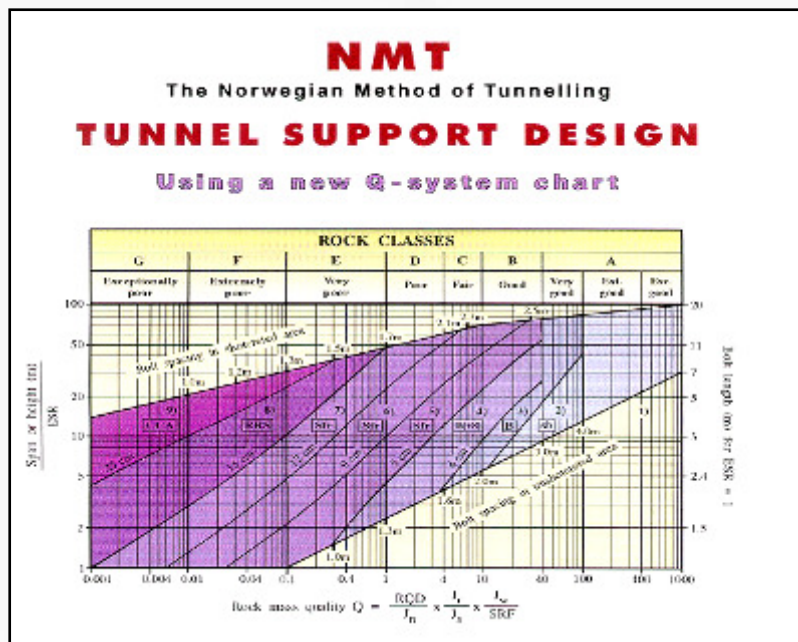


Rock Mass Classification

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

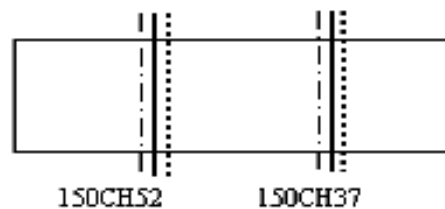
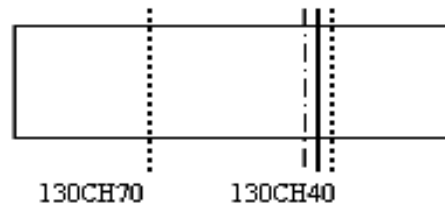
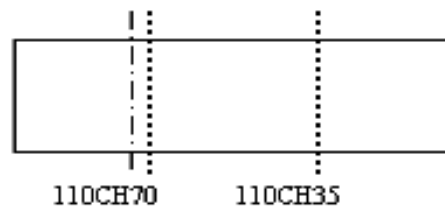
Tunnel Support Design

- Empirical method for preliminary design
- Numerical modelling for optimisation and special cases
- Instrumentation & monitoring for design and performance verification

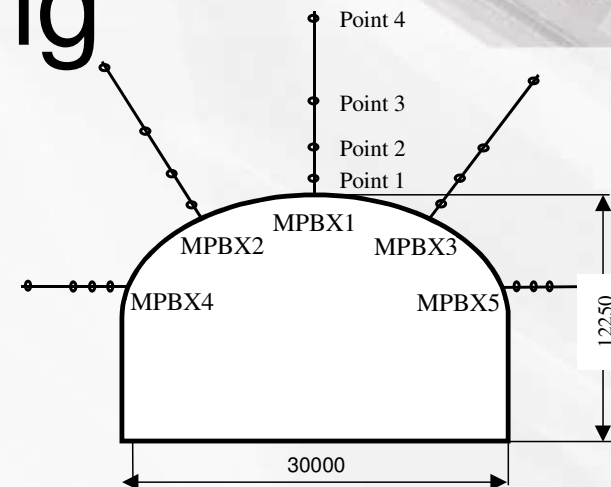


Principal Stress Distribution
Around Two Tunnels

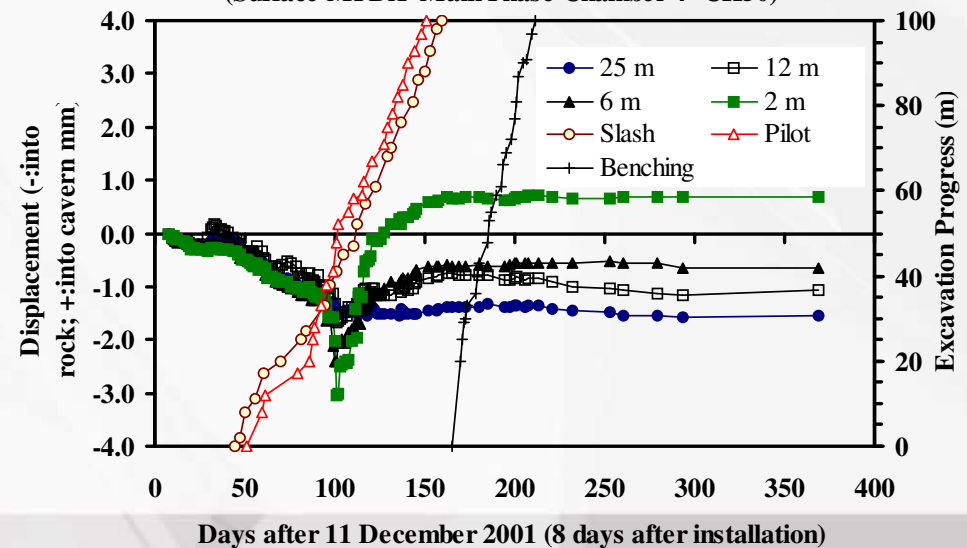
Instrumentation and Monitoring



- Convergence monitoring section
- MPBX monitoring section
- Bolt load monitoring section

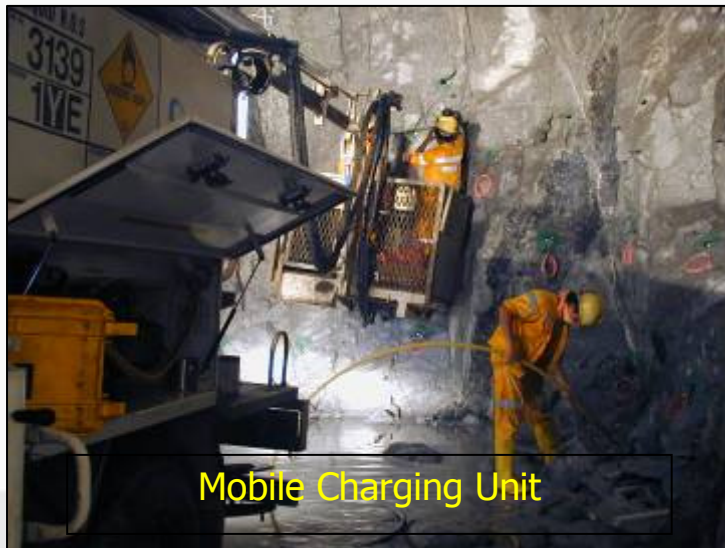


Displacement and Progress
(Surface MPBX Main Phase Chamber 4--CH50)



Blasting 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 blasting
- Reduced emission of toxic gas and ventilation time

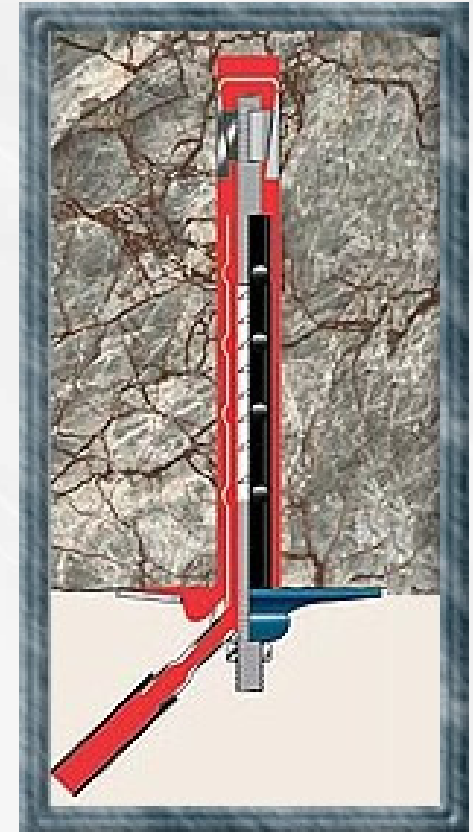
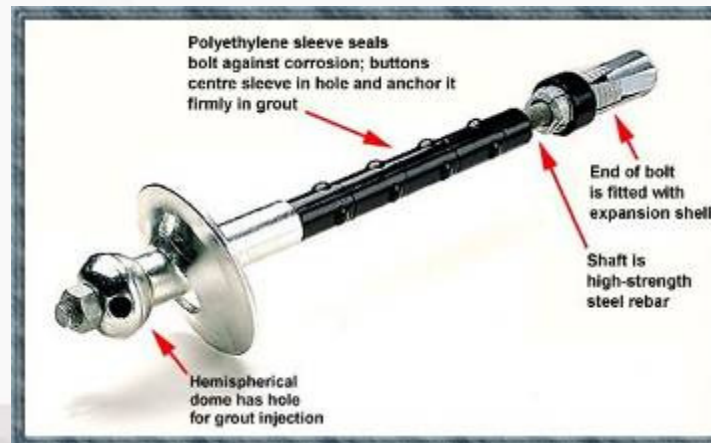


Rock Support and Reinforcement

- Temporary support part of permanent support
- SFR Shotcrete used as temporary support (*Not a standard practice in NMT*)
- Spiling bolts in heavily jointed zones
- CT-bolts installed (end anchor only) during face drilling for subsequent rounds
- Grouting of CT bolts done later
- *Norwegian preference is for permanent support behind the advancing face using separate equipment and crew*

Use of Rock Bolts

- Corrosion protection (polyurethane sleeve, galvanising, cement grout, etc)
- CT Bolts preferred by operators to rebar (lack of physical strength, safety concern)
- Pattern bolting or “blind” bolting ?(angled bolts, penetration at rock joints)
- Cost (material cost small component)
- *Norwegian preference for cheaper rebars for grouted bolts*



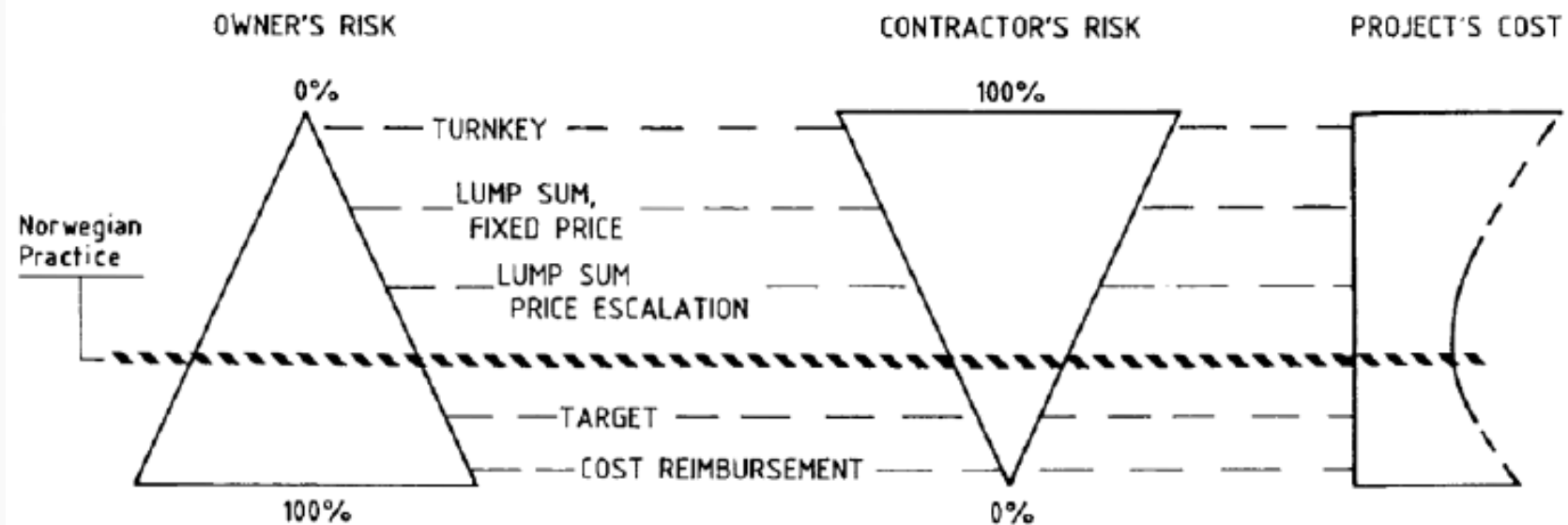
Steel Fibre Reinforced Shotcrete

- Wet mix (*considered a key feature of NMT*)
- Steel fibre: 45 kg /m³
- 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. Joules)

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

Norwegian Concept of Risk Sharing



- Owner - responsible for ground conditions, site investigation results, and the concept
- Contractor - responsible for performance to specifications

Source: Norwegian Tunnelling Society, 2004

Engineering Geology Report



- Comprehensive report with geological model, anticipated ground behaviour, and expected rock reinforcement
- Specific data on geological setting, structural geology, geological profiles, ground water, rock mass permeability, in situ stress, basic rock mechanics data, rock mass classifications

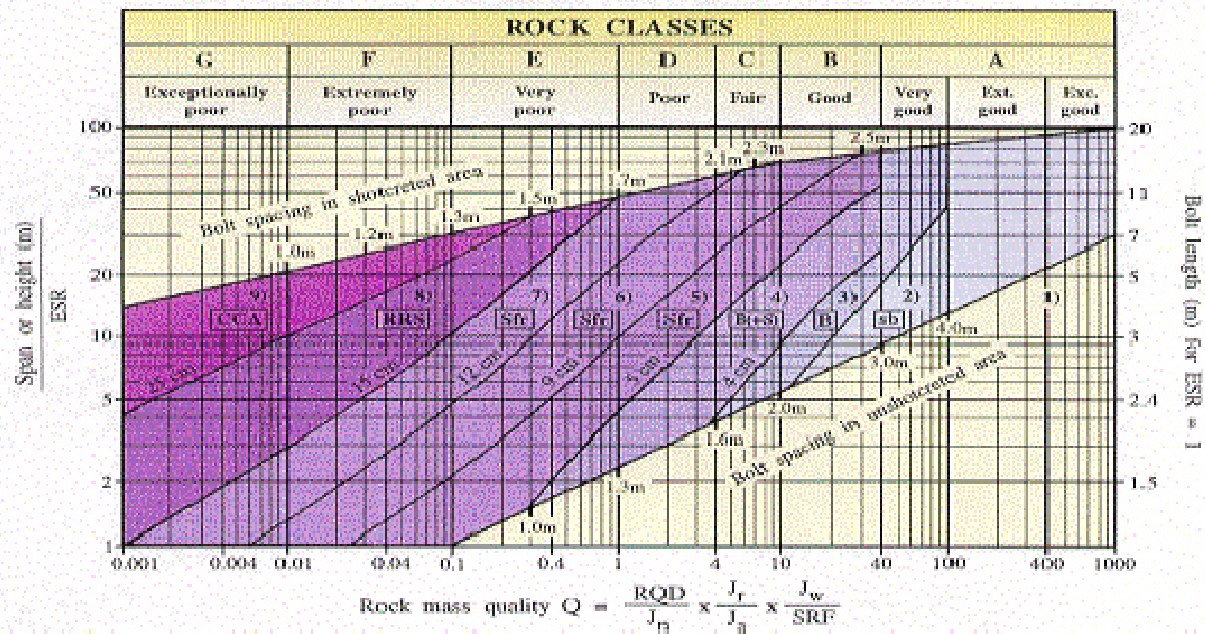
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Use of “NMT”

- Mutual agreement on “tunnelling system”
- Principles of Norwegian Method of Tunnelling:
 - Engineering geology report as basis for estimates
 - Unit prices for various rock conditions; client pay according to actual rock conditions;
 - Preliminary design
 - Detailed design decided during excavation after tunnel mapping
 - Close collaboration between geologists of contractor and client
 - Forum for resolving differences on site
 - Emergency power to contractor for adverse conditions

Support Design Using Q-chart



REINFORCEMENT CATEGORIES:

- | | |
|--|--|
| <ul style="list-style-type: none"> 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 | <ul style="list-style-type: none"> 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 |
|--|--|

Typical Rock Support

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

Phasing of Rock Excavation

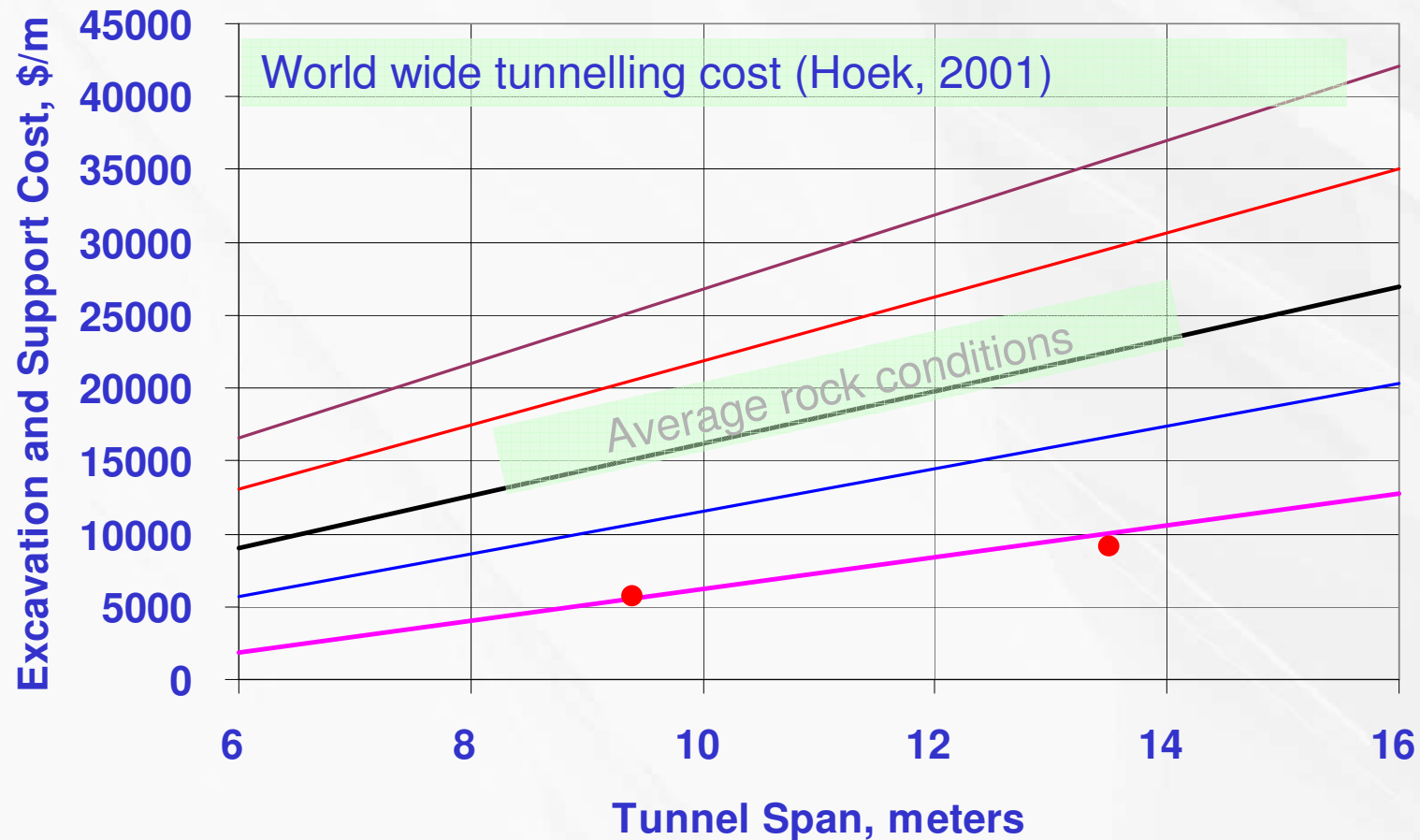


■ Pilot phase - cost plus contract

- Appreciation of geological conditions and rock mass quality and effectiveness of excavation method and rock support
- Data on cost, unit rates, and time
- Verification of design assumptions and tunnel performance
- Feedback for modifications of design and technical specifications
- **Agreed use of “NMT” with consultant and contractor**
- **Technology transfer**

■ Main phase - lump sum with unit rates

Comparison of World-wide Cost

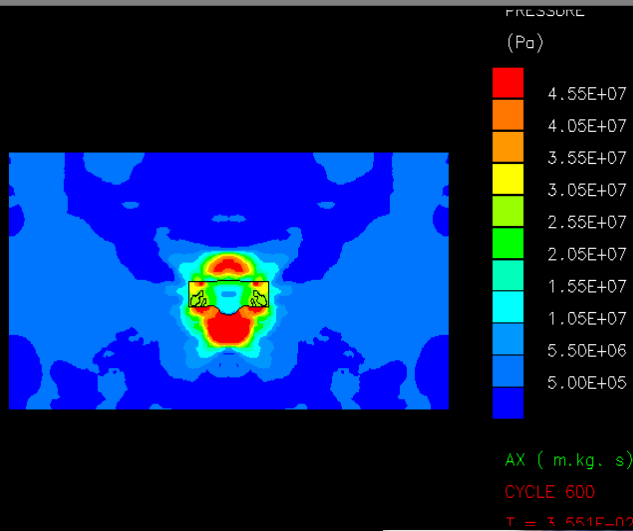


- Competitive cost in Singapore due primarily to a) large tunnel sections; b) good rock; and c) low labour cost

TECHNOLOGY DEVELOPMENT

Technology Development Approach

Numerical Modelling

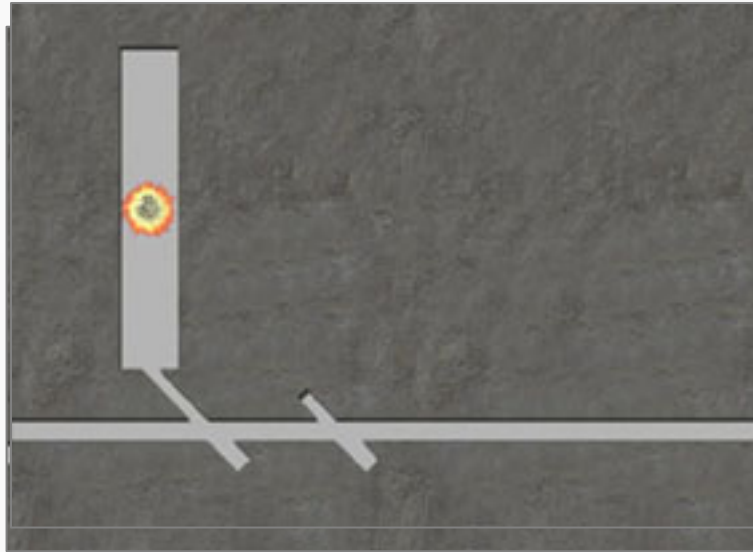


Small-scale Testing

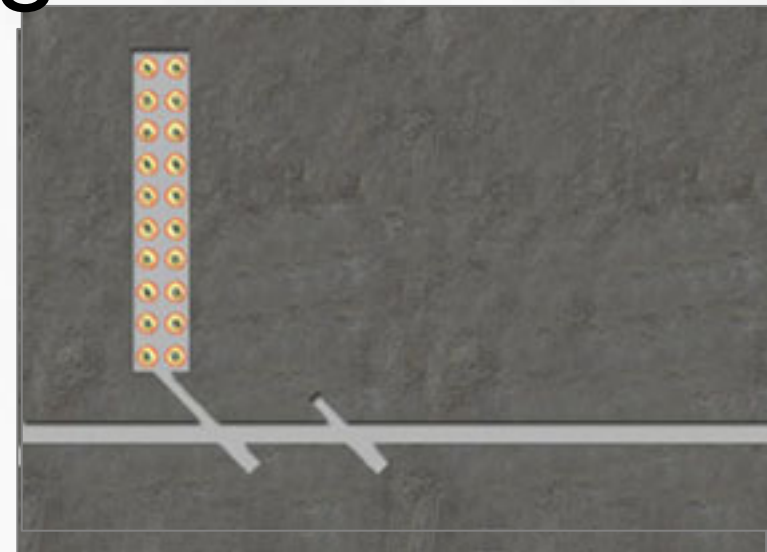


Large-scale Testing

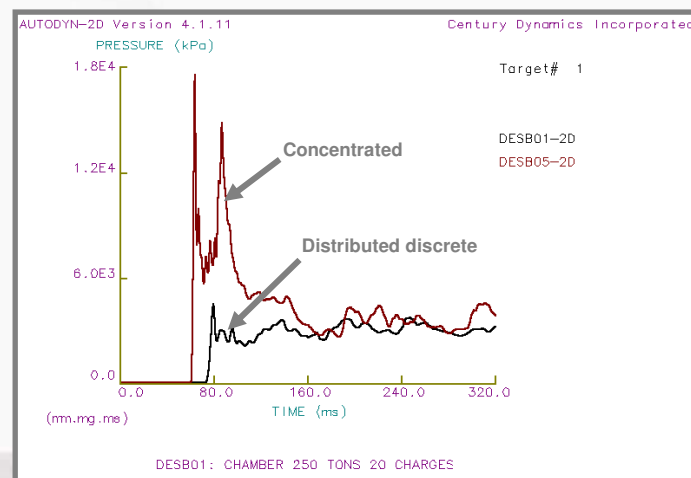
Realistic Explosion Effects Modelling



Concentrated Charge



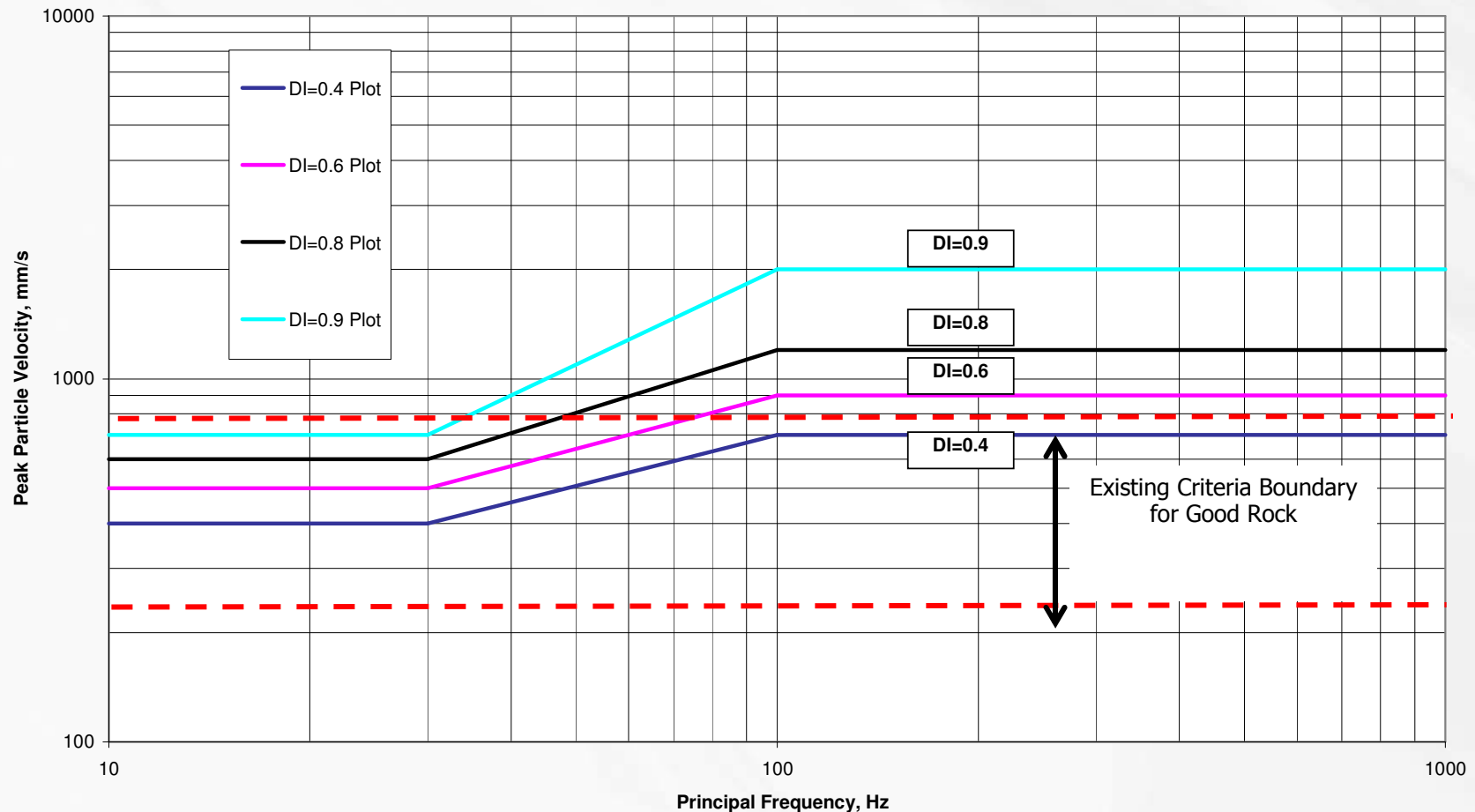
Distributed Discrete Charge



2 to 3 times
difference

Frequency-Based Damage Criteria

Damage Contour Plot for RC Buildings up to Ten -Storey



New criteria for ground shock endorsed by NATO Underground Storage Working Group

Blast Door Structural Response Test at DTRA, USA



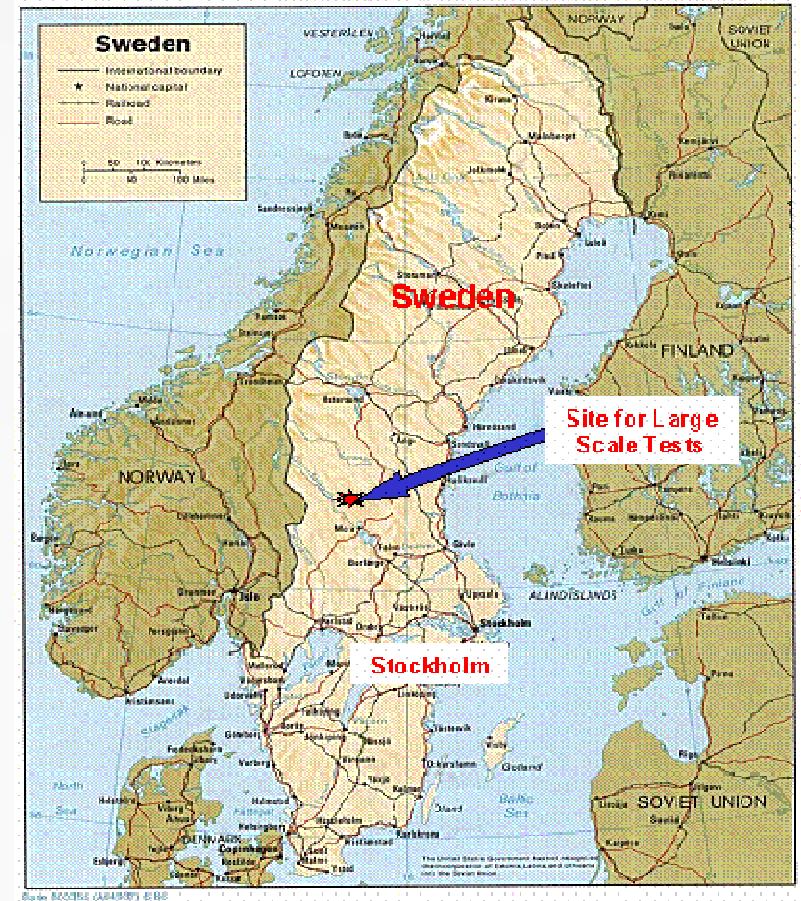
Shot	Load	Objective	Test
1	Calibration	Calibration	Bare Charge
2	Under load	Verify elastic behaviour	HEST
3	Design load	Verify structural response at design load	HEST
4	Over load	Verify structural response at close to failure load	HEST

**HEST – High Explosive Simulation Test*



Large-scale Tests in Sweden

- Collaboration with Swedish Defence Research Agency and Armed Forces HQ, with participation from NDEA, Norway
- Validation of underground facility design
 - Airblast propagation
 - Door pressure and response
 - Ground shock
 - Debris hazards
 - Response of tunnels (at criterion distances)



LST UAF – Tests Conducted



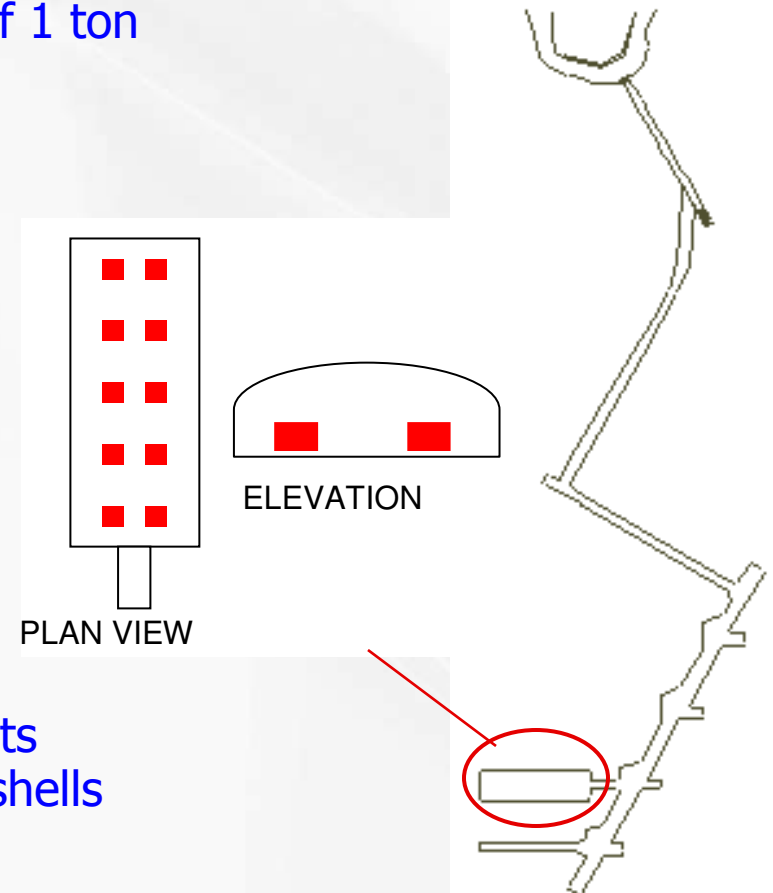
10-t TNT bare charge,
distributed in 10 cubes of 1 ton
each



Worst-case scenario for
debris hazard



Mixed storage: propellants
surrounded by 155 mm shells



Collaboration and Technology Transfer

Norwegian Technology in the Project



Getting ready for stress measurements (SINTEF)



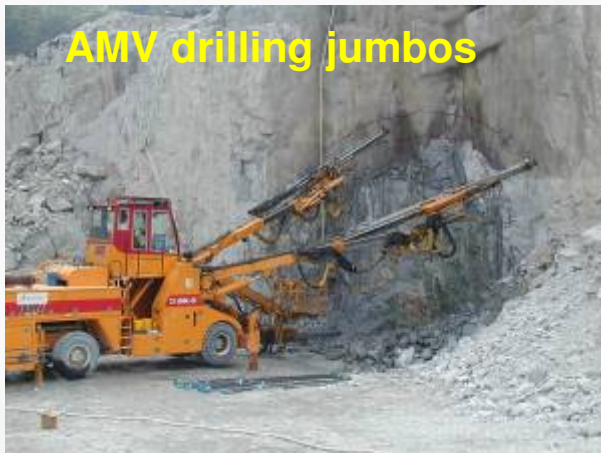
Giertsen cavern liners



Instrumentation & monitoring, NTU & NGI



AMV drilling jumbos



Ørstå CT-bolts



Working as Team

NI geologist at work



Safety briefing



Training of local drillers



It's not all work!



A friendly soccer match



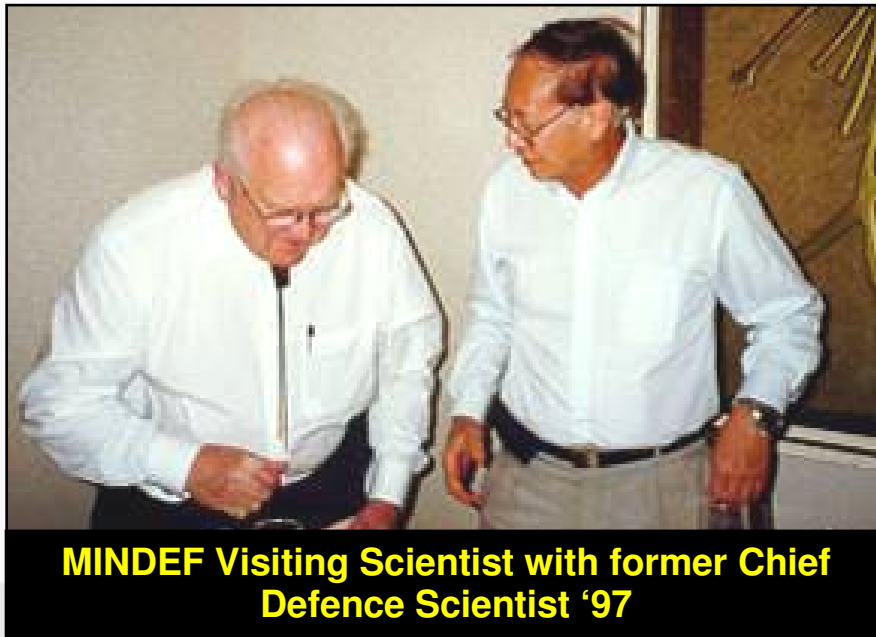
Collaborations & Technology Transfer



Norwegian Defence Estates Agency	R&D collaboration in protective technology. technical workshops; visits to underground defence facilities; review of UAF concepts; NATO UG Storage Working Group
Norwegian Geotechnical Institute	Instrumentation for convergence and deformation measurements for the UAF through a DSTA-NTU joint R&D project
SINTEF	3-D stress measurements in the pilot phase through a DSTA-NTU joint R&D project
Norconsult International AS	Specialist consultant in rock engineering and protective design to STAE
Selmer AS	In joint venture with Sembcorp Engineers and Constructors in the pilot phase rock excavation
Ørstå Stalindustri AS	Supplier of speciality rock bolts to SCEC
Andersens Mek. Verksted AS (AMV)	Supplier of 3-boom computerised rock drilling jumbos to SCEC
Giertsen	Subcontractor to SCEC in supplying and installing water-proof chamber lining systems

Letter of Intent

- Joint R&D in protective technology
- Security Agreement covering LOI allows sharing of sensitive information and visits to classified sites



Exchange of LOI in Norway '98



Workshop in Jan 2003



- Defence and protection requirements
- Storage, transportation, and shelters
- Oil and gas storage
- Water and sewage
- Telecommunications and supply of electricity
- Education and technology development



Important Issues in Collaboration

- Understanding local culture and conditions
- Technology transfer
- Build up of in-house capability
- Security

Thank You!