NORDIC SUB SEA TUNNEL PROJECTS

Olav Torgeir Blindheim
Dr ing O T Blindheim, Oslo, Norway

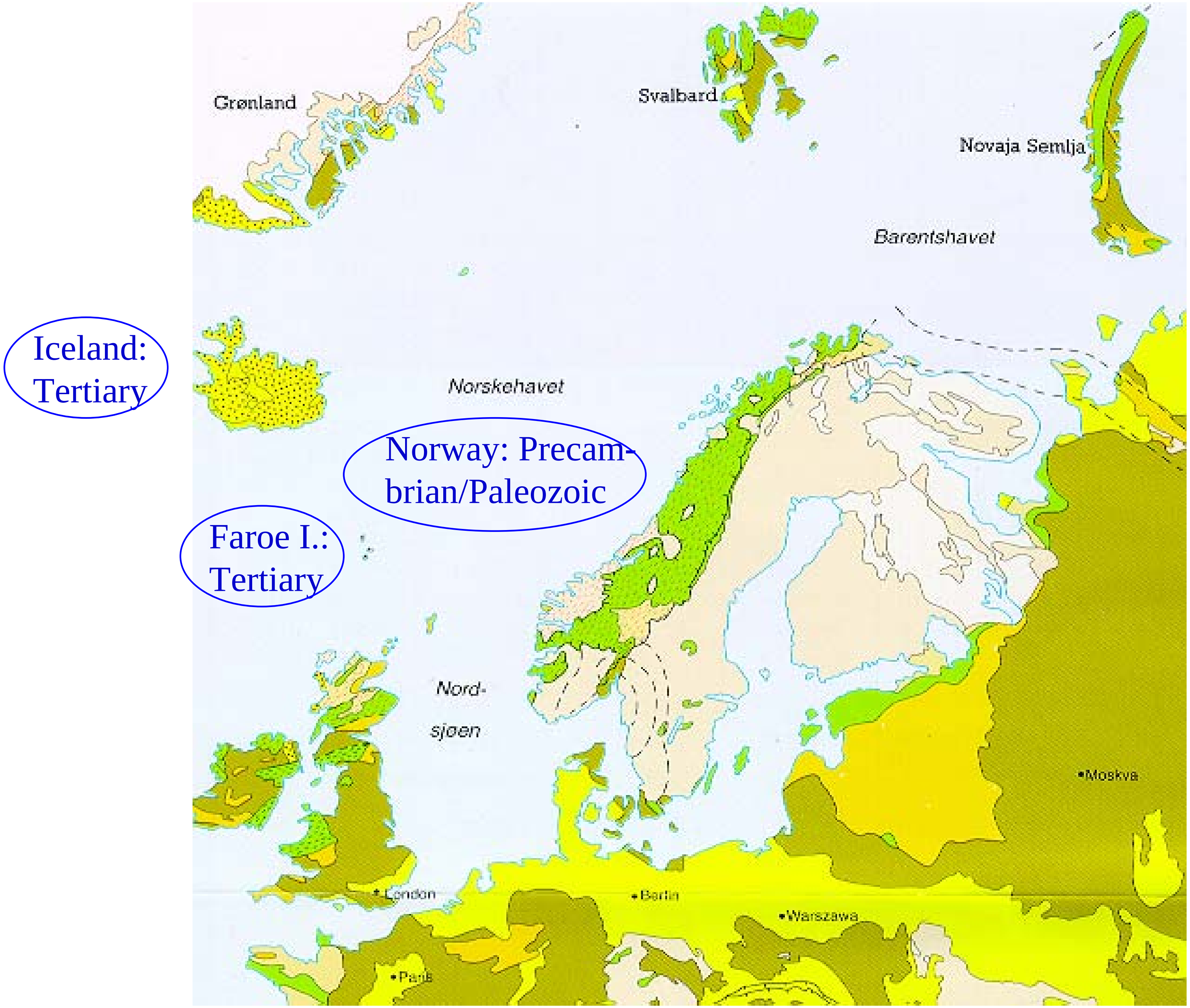
Eivind Grøv
SINTEF Rock and Soil Mechanics, Trondheim, Norway

Bjørn Nilsen
Norwegian University of Science and Technology (NTNU)
Trondheim, Norway

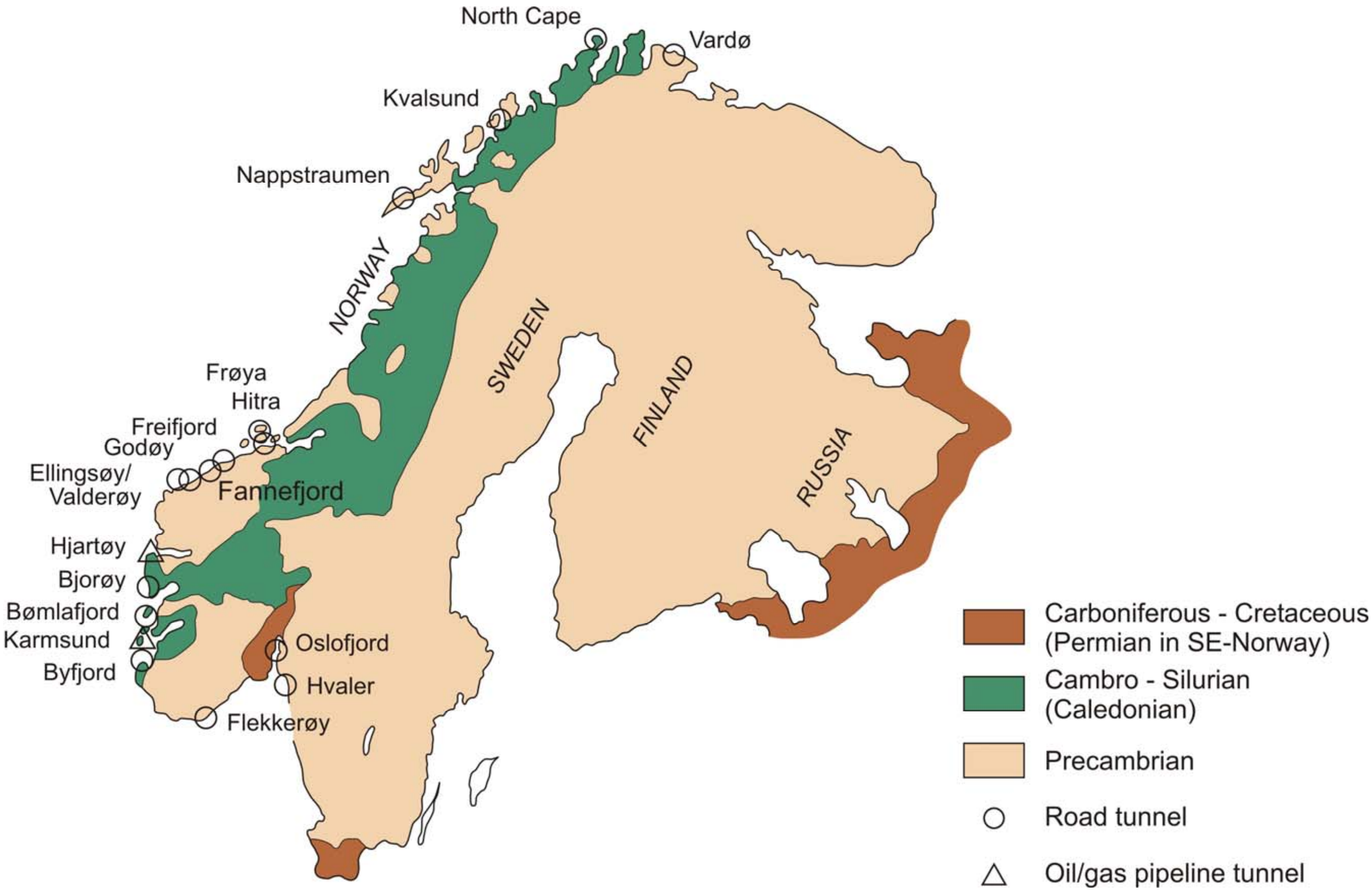
OUTLINE OF PRESENTATION

- GEOLOGICAL OVERVIEW
- COMPLETED NORWEGIAN PROJECTS
  - Road tunnels
  - Tunnels for oil, gas and water
- BASIC PRINCIPLES OF NORWEGIAN TUNNELS / LESSONS LEARNED
  - Characteristics and main challenges
  - Geo-investigations
  - Excavation
  - Rock support
  - Water control
  - Operational experience
- PROJECTS IN ICELAND AND FAROE ISLANDS
- FUTURE DEVELOPMENTS

GEOLOGICAL OVERVIEW



LOCATIONS OF MAIN NORWEGIAN SUB SEA TUNNELS



NORWEGIAN SUB SEA ROAD TUNNELS - KEY DATA OF MAIN PROJECTS

PROJECT	YEAR	AREA (m^2)	GEOLOGY	LENGTH (km)	MIN. ROCK COVER (m)	DEPTH (m.b.s.l.)
Vardø	1981	53	Shale/sandst.	2.6	28	- 88
Ellingsøy	1987	68	Gneiss	3.5	42	-140
Kvalsund	1988	43	Gneiss	1.6	23	- 56
Godøy	1989	52	Gneiss	3.8	33	-153
Nappstraumen	1990	55	Gneiss	1.8	27	- 60
Freifjord	1992	70	Gneiss	5.2	30	-100
Byfjorden	1992	70	Phyllite	5.8	34	-223
Hitra	1994	70	Gneiss	5.6	38	-264
North Cape	1999	50	Shale/sandst.	6.8	49	-212
Oslofjord	2000	78	Gneiss	7.2	32	-130
Frøya	2000	52	Gneiss	5.2	41	-157
Bømlafjord	2000	78	Gneiss/schist	7.9	35	-260
Skatestraum	2002	52	Gneiss	1.9	40	- 80
Eiksund	2007	71	Gneiss/gabbro/ limestone	7.8	50	-287

TOTAL NUMBER: 25

VARDØ SUB SEA ROAD TUNNEL, 1981

NAPPSTRAUMEN SUB SEA ROAD TUNNEL, 1988

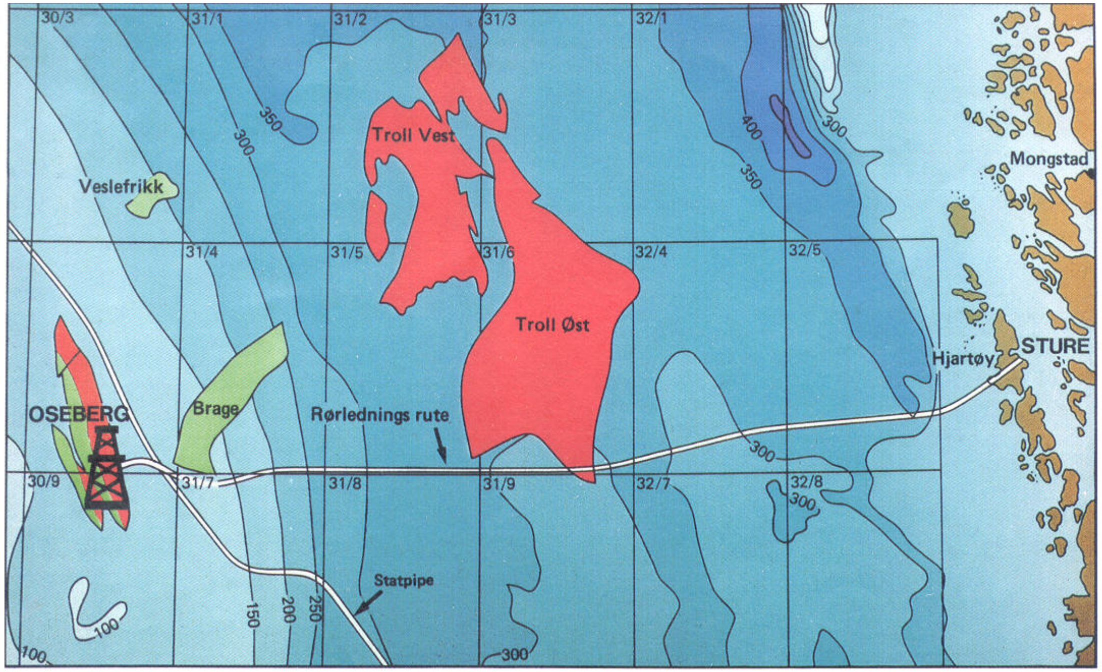
OSLOFJORD SUB SEA ROAD TUNNEL, 2000

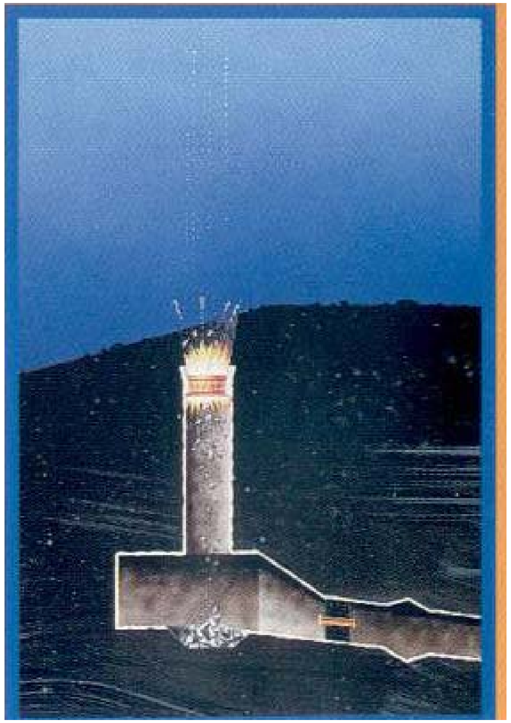
NORWEGIAN SUB SEA TUNNELS FOR WATER, GAS AND OIL - KEY DATA OF MAIN PROJECTS

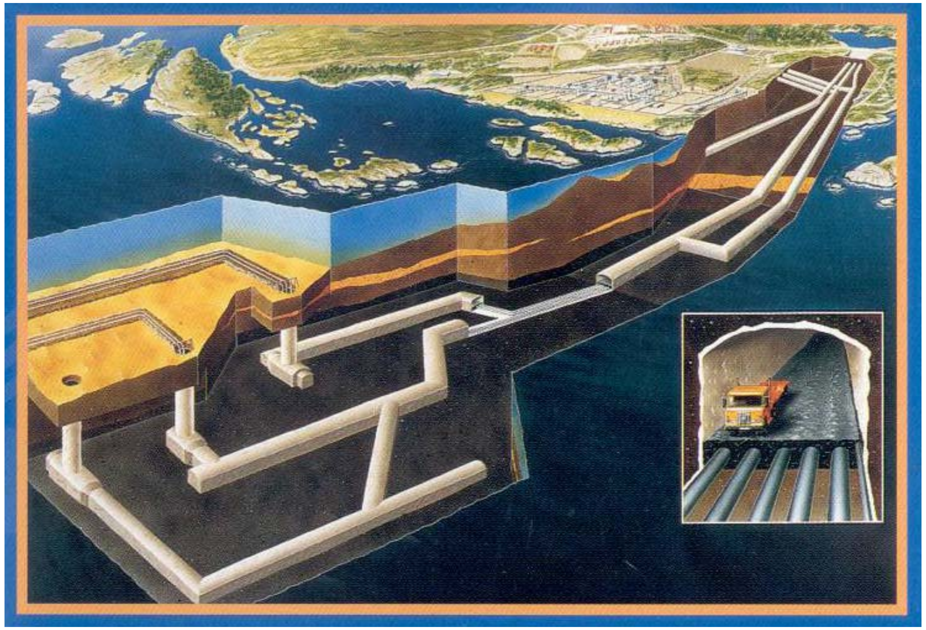
PROJECT	YEAR	AREA (m^2)	GEOLOGY	LENGTH (km)	MIN. ROCK COVER (m)	DEPTH (m.b.s.l.)
Frierfjord (gas)	1976	16	Gneiss/clayst.	3.6	48	-253
Karmsund (gas)	1984	27	Gneiss/phyllite	4.7	56	-180
Førdesfjord ”	1984	27	Gneiss	3.4	46	-160
Førlandsfjord ”	1984	27	Gneiss/phyllite	3.9	55	-170
Hjartøy (oil)	1986	26	Gneiss	2.3	38 (6)	-110
Kollsnes (gas)	1994	45-70	Gneiss	3.8	7 (piercing)	-180
Snøhvit (water)	2005	22	Gneiss	1.1/3.3		-111/54
Aukra ”	2005	20/25	Gneiss	1.4/1.0		- 86/57

TOTAL NUMBER: 16

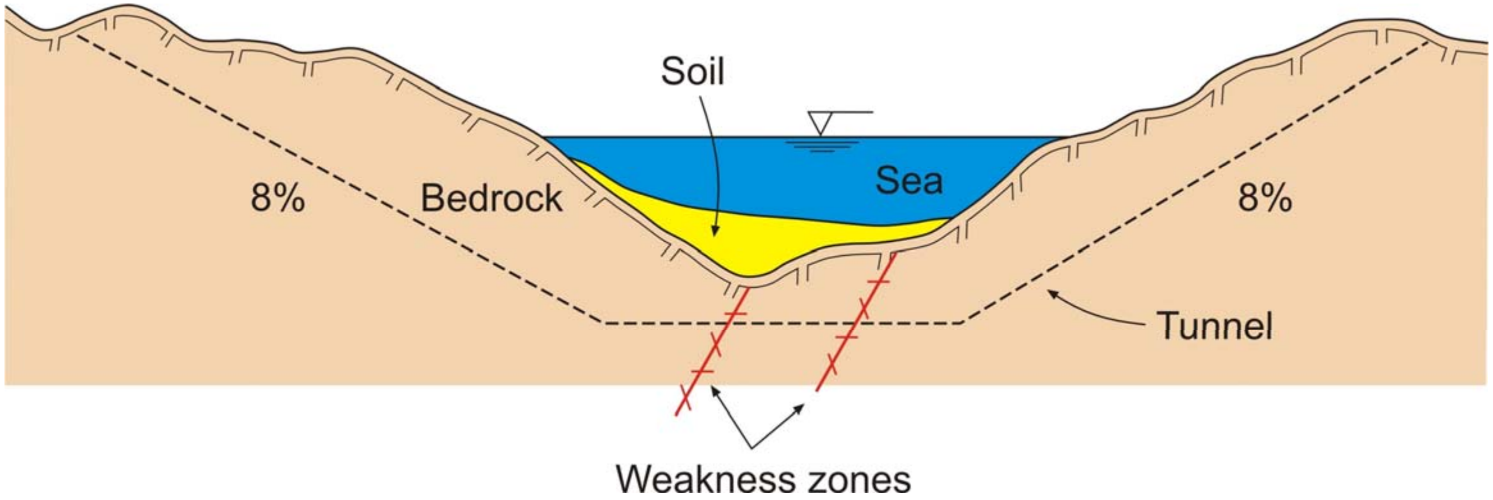
KOLLSNES (TROLL)
GAS PIPELINE TUNNEL, 1994





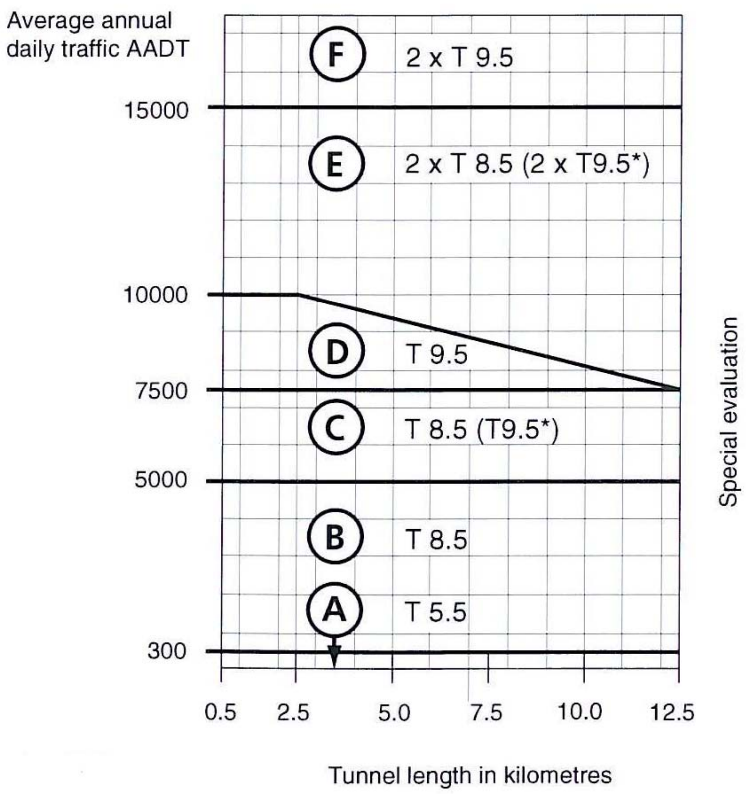


MAIN CHALLENGES OF TYPICAL FJORD CROSSING TUNNEL



- PROJECT AREA COVERED BY WATER
- OFTEN MAJOR FAULTS / WEAKNESS ZONES
- INCLINED FROM BOTH SIDES
- UNLIMITED LEAKAGE RESERVOIR
- SALINE LEAKAGE WATER

NORWEGIAN SUB SEA ROAD TUNNELS: CLASSIFICATION ACCORDING TO NPRA (2002)



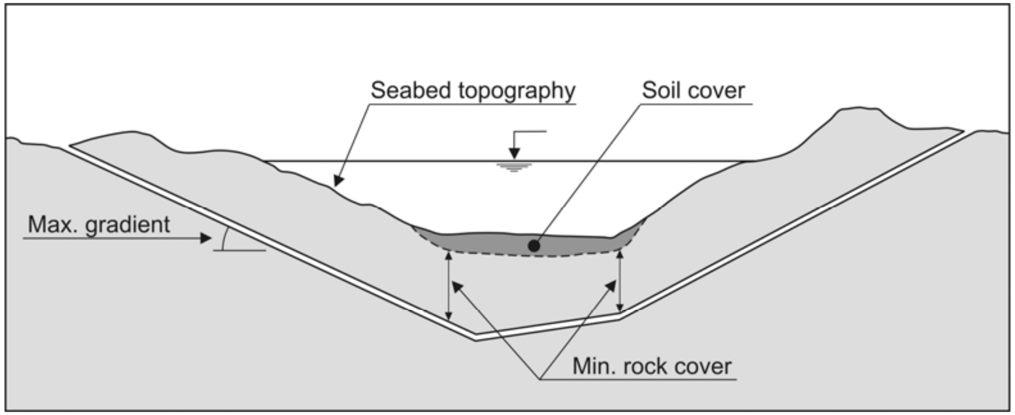
TUNNEL CLASS DEFINES REQUIREMENTS FOR:

- VENTILATION
- ILLUMINATION
- COMMUNICATION
- EMERGENCY SYSTEM
- ELECTRICAL SUPPLY
- CONTROL SYSTEM

COST: 6,000-10,000 USD/m

FINANZED BY TOLL FEES (AND SUBSIDIZED)

REQUIREMENTS CONCERNING GRADIENT AND MINIMUM ROCK COVER (NPRA)



2 LANES: MAX. GRADIENT 8%

3 LANES: MAX. GRADIENT 10% (OFTEN IN UP-SLOPES)

MINIMUM ROCK COVER: 50m, UNLESS FAIR ROCK MASS CONDITIONS HAVE BEEN PROVED

GEO-INVESTIGATION PRIOR TO EXCAVATION

TYPICALLY A FIVE-STEP PROCEDURE:

1) REVIEW OF BACKGROUND INFORMATION

2) ON SHORE FIELD MAPPING

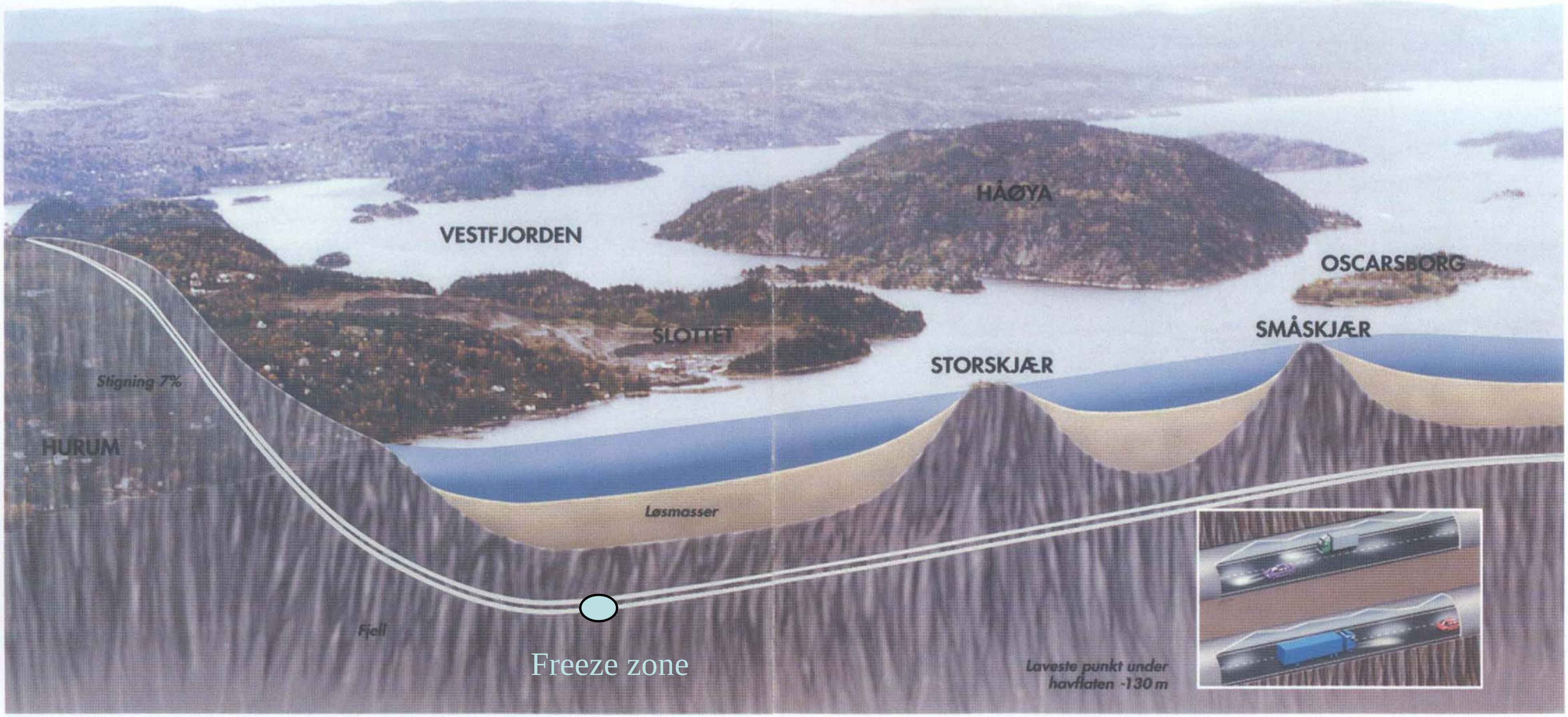
3) ACOUSTICAL PROFILING

4) REFRACTION SEISMIC PROFILING

5) DRILLING

INVESTIGATION COST: ~5-10% OF EXCAVATION COST

OSLOFJORD SUB SEA ROAD TUNNEL



Oslofjordforbindelsen er en ferjefri kryssing av Oslofjorden mellom E6 i Frogn og E18 ved Lier/Drammen. Forbindelsen vil føre til en betydelig bedret infrastruktur i Østlandsregionen, og ha stor trafikk- og miljømessig betydning for vegnettet i hele området.

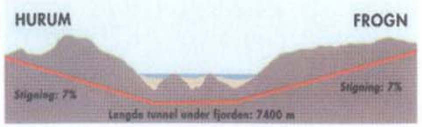
Gjennom bygging av Oslofjordforbindelsen åpnes en ny hovedkorridor for nærings-utvikling sør for Oslo. Den knytter områdene øst og vest for fjorden sammen, skaper raskere kommunikasjoner mot Sverige og kontinentet, og avlaster de sentrale deler av Oslo - området ved å åpne nye områder for utbygging.

Oslofjordforbindelsen er planlagt bygd ut som en 7,4 km lang fjelltunnel under fjorden. Når den står ferdig vil den bli verdens lengste undersjøiske vegtunnel.

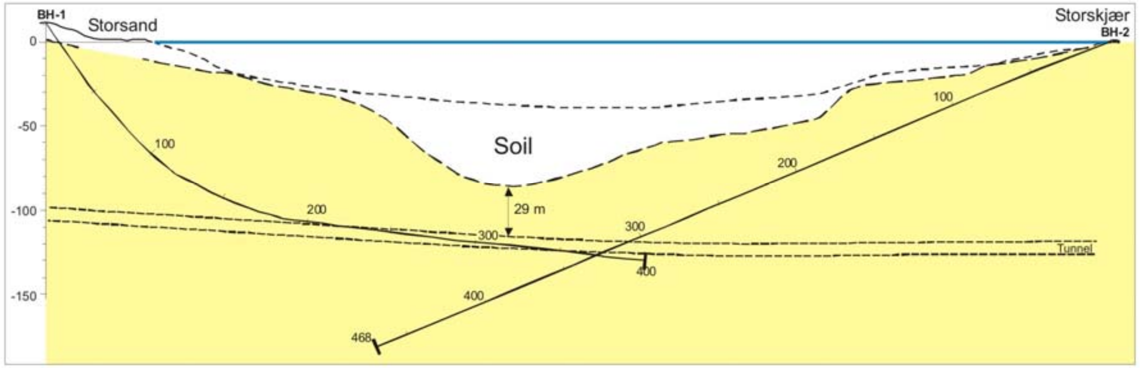
TEKNISKE DATA

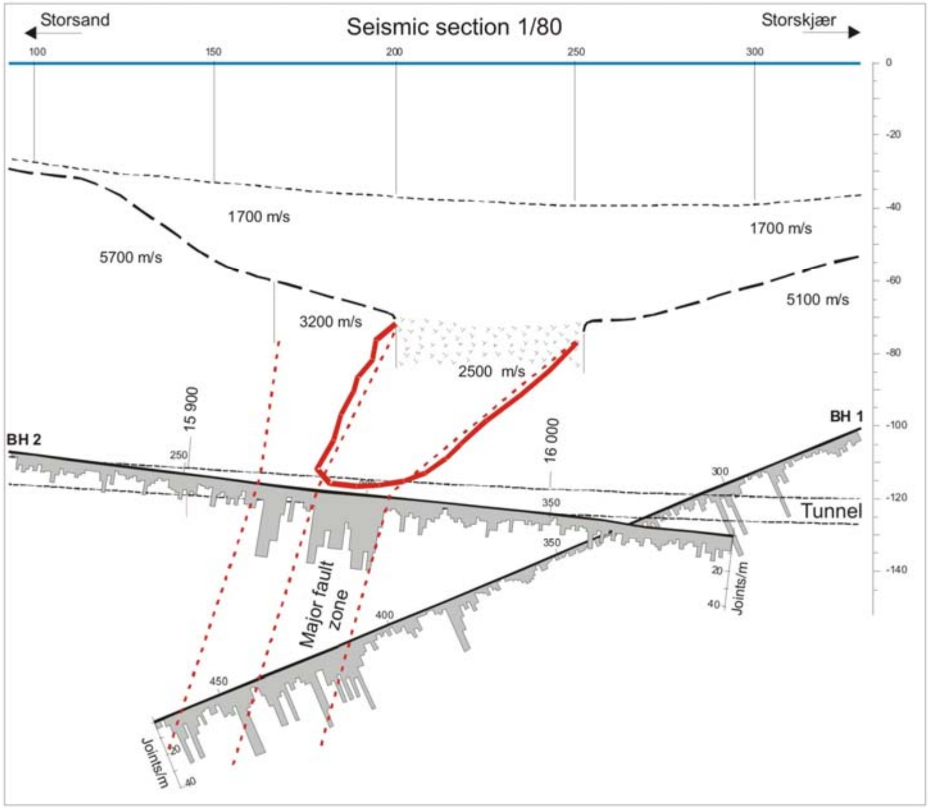
Total lengde: ....26,9 km
- av dette utgjør tunneler: ....9,8 km, eller ca.36 % av lengden
- og bruer: ....830 m
Vegbredde: ....10 m
Oslofjordtunnelens lengde: ....7400 m
Største stigning: ....7 %
Laveste punkt under havflaten: ....-130 m
Tverrsnitt: .... 2 tunnelløp, hvert med 2 kjørefelt.

Byggekostnad: ....1.270 mill.kr.(1994)
- herav Oslofjordtunnelen: .... 655 mill.kr.
Byggetid Oslofjordtunnelen: ....ca. 3 år
Byggetid veger på land: ....ca. 2 år



ERODED CHANNEL, OSLOFJORD SUB SEA ROAD TUNNEL





EXCAVATION METHOD

DRILL AND BLAST USED FOR ALL PROJECTS, DUE TO:

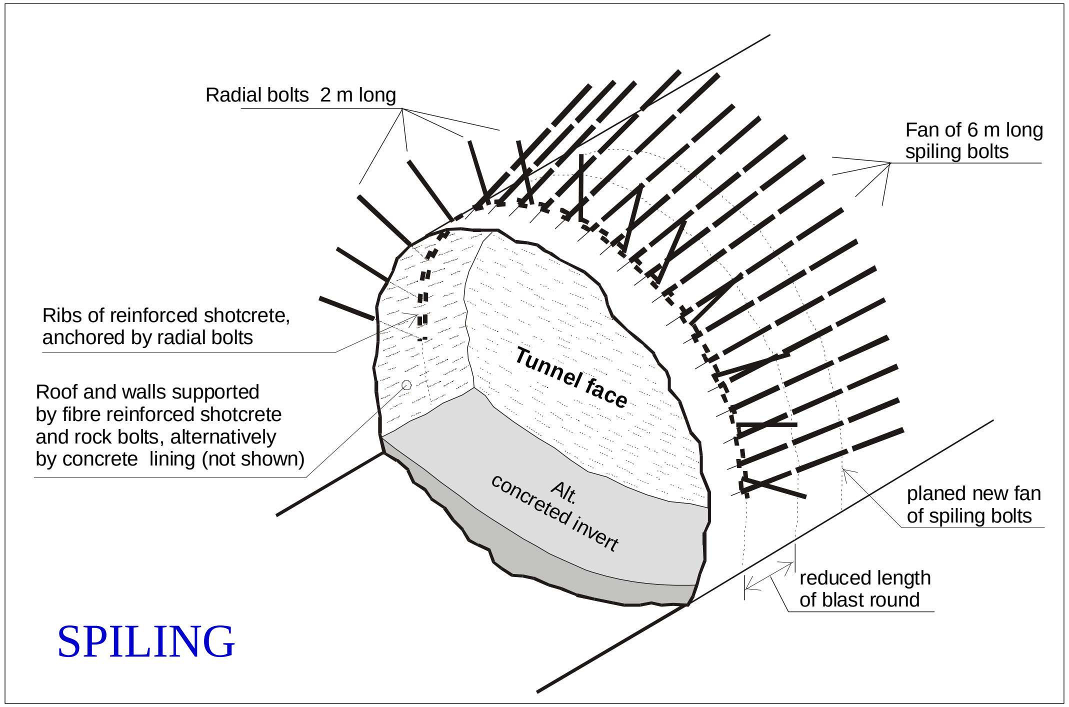
- GREAT FLEXIBILITY
- COST EFFECTIVENESS

TRADITIONAL UNIT RATE CONTRACT MOST COMMON

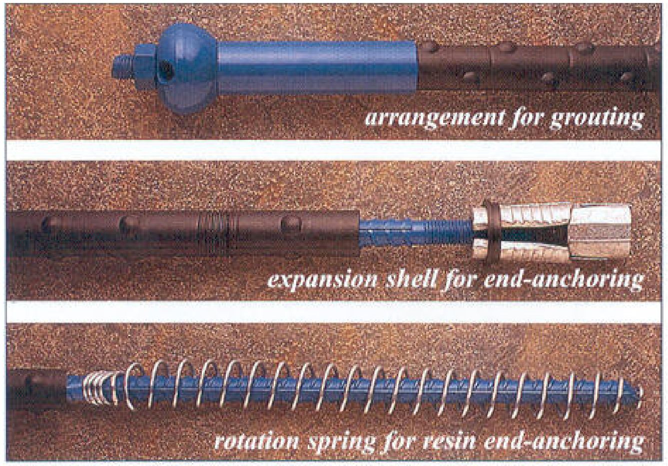
EXTENT OF ROCK SUPPORT

TUNNEL	EXCAV. RATE (m/week)	BOLTS (nos./m)	SHOTCRETE m^3/tm	CONCRETE LINING rel.%	GROUTING (cement) kg/m
Vardø	17	6.9	0.95	21	31.7
Karmsund	34	1.5	0.72	15	13.4
Ellingsøy	28	6.4	0.48	3	99.1
Kvalsund	56	4.0	0.31	0	0
Freifjord	45	5.3	1.44	2.1	13.7
Hitra	46	4.2	1.44	0.2	11.4
North Cape	18/56	3.4	4	34	10
Oslofjord	47	4.0	1.7	1	165
Frøya	37	5	2.9	5	197
Bømlafjord	55	3.8	1.9	0	36

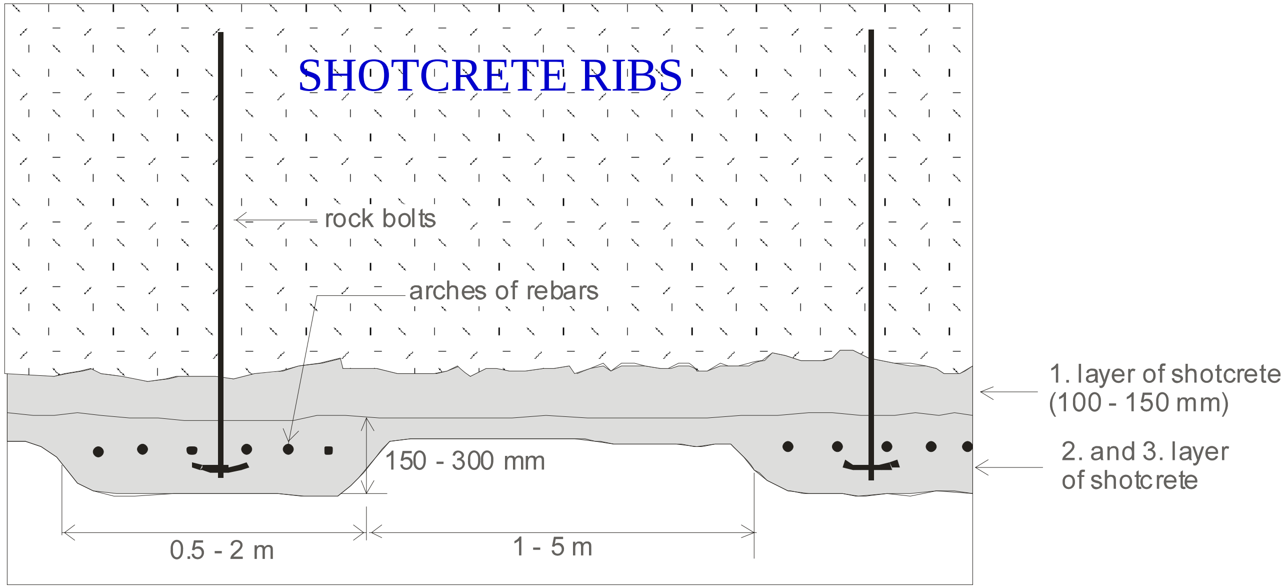
ROCK SUPPORT IN DIFFICULT GROUND CONDITIONS



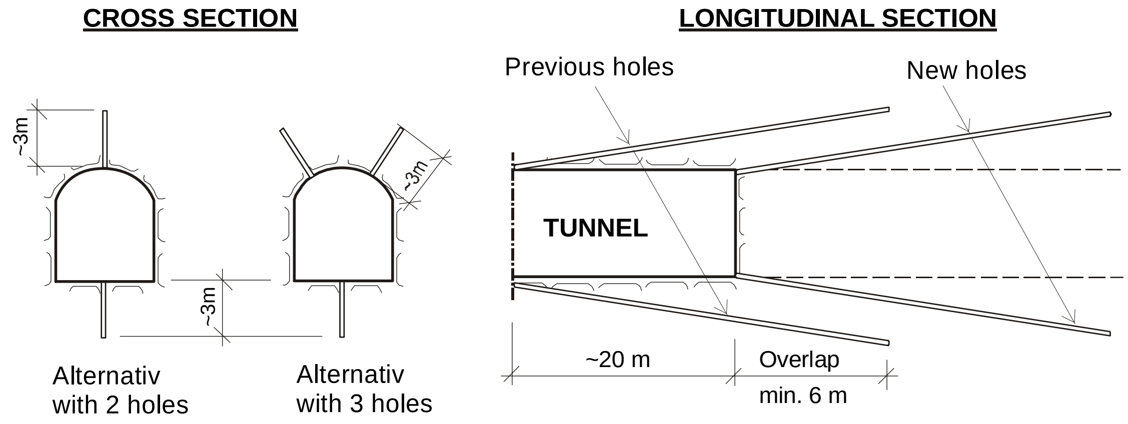
SPILING



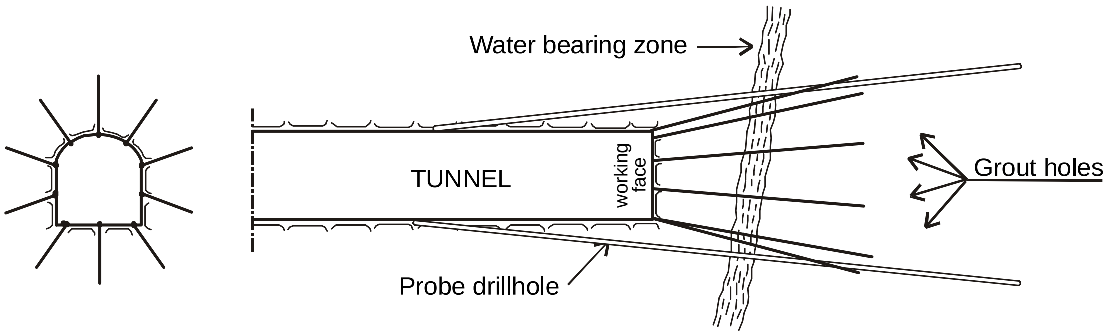
CT-BOLT



WATER CONTROL



1) PROBE DRILLING



2) PRE-GROUTING

GROUTING PRESSURE UP TO 10 MPa

PRESET QUANTITY FOR ECONOMICAL PUMPING: ~300 l/min per km

ACHIEVED AT OPENING: 20-460 l/min per km

OPERATIONAL EXPERIENCE

- WATER INGRESS REDUCED BY UP TO 50% (SELF SEALING)
- ALGEA GROWTH IN SOME TUNNELS
- PERIODICAL REPLACEMENT OF INSTALLATIONS REQUIRED
- ACCIDENT RATE LESS THAN ON OPEN ROADS
- 3 CASES OF FIRE, NONE WITH PERSONAL INJURY

PROJECTS IN ICELAND AND FAROE ISLANDS

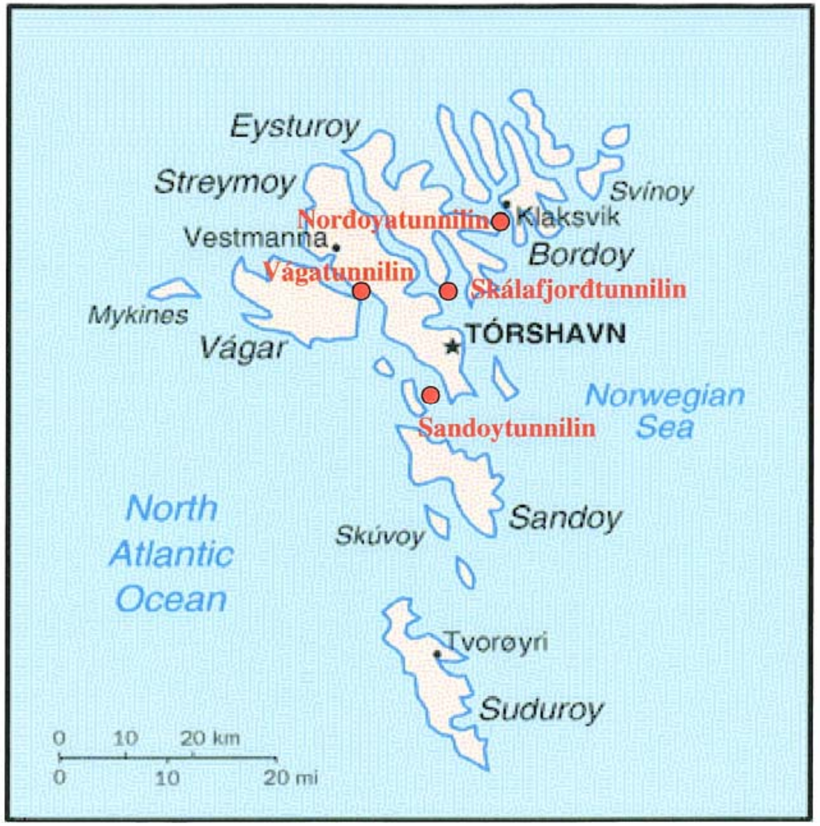
PROJECT	YEAR	AREA (m^2)	GEOLOGY	LENGTH (km)	MIN. ROCK COVER (m)	DEPTH (m.b.s.l.)
Hvalfjördur	1998	55/65	Basalt	5.8	38	-165
Vága	2002	65	Basalt	4.9	30	-105
Nordoya	2006	43	Basalt	6.2	35	-165

PLANNED AND BUILT ACCORDING TO THE NORWEGIAN CONCEPT

HVALFJORDUR SUB SEA ROAD TUNNEL (1998)

- BOOT-PROJECT (Spölur hf), 20 YEARS => IPRA
- SEISMIC ACTIVE AREA => RISK ANALYSIS ESSENTIAL
- ESTIMATED: 1800 AADT => CURRENTLY 4200 AADT

VÁGA (2002) AND NORDOYA SUB SEA ROAD TUNNELS (2006)



- VOLCANIC ROCKS, SEISMICALLY STABLE
- SECTIONAL COMPLETION => SHORTER CONSTRUCTION TIME
- STRONG FOCUS ON HS
- 2 MORE TUNNELS BEING CONSIDERED

FUTURE DEVELOPMENTS

- MANY MORE SUB SEA TUNNELS IN NORWAY, INCLUDING LONGER AND DEEPER:

  Rogfast: 24 km / 400 m.b.s.l.

  Hareid-Sula: 17 km / 630 m.b.s.l.

- SIMILAR PROJECTS IN OTHER REGIONS:

  Shetland Islands

  Orkneys

  Greenland

  Åland

- ADAPTATION TO EU TUNNEL SAFETY DIRECTIVES

  TERN-tunnels: Max. gradient 5%

  TERN-tunnels with AADT>4000: special requirements concerning safety

Risk analysis and ground investigations
Bjørn Nilsen, Norwegian University of Science and Technology (NTNU)

GEO-INVESTIGATIONS PROVIDE THE BASIS FOR

- SELECTING TUNNEL ALIGNMENT AND DESIGN
- EVALUATION OF ENVIRONMENTAL IMPACT
- PLANNING OF EXCAVATION METHODS, SUPPORT AND WATER SEALING
- COST AND SCHEDULE ESTIMATION
- TENDERING
- CONTROL AND FOLLOWING UP DURING CONSTRUCTION

PRE-CONSTRUCTION GEO-INVESTIGATIONS

TYPICALLY A FIVE-STEP PROCEDURE:

1) REVIEW OF BACKGROUND INFORMATION

2) ON SHORE FIELD MAPPING

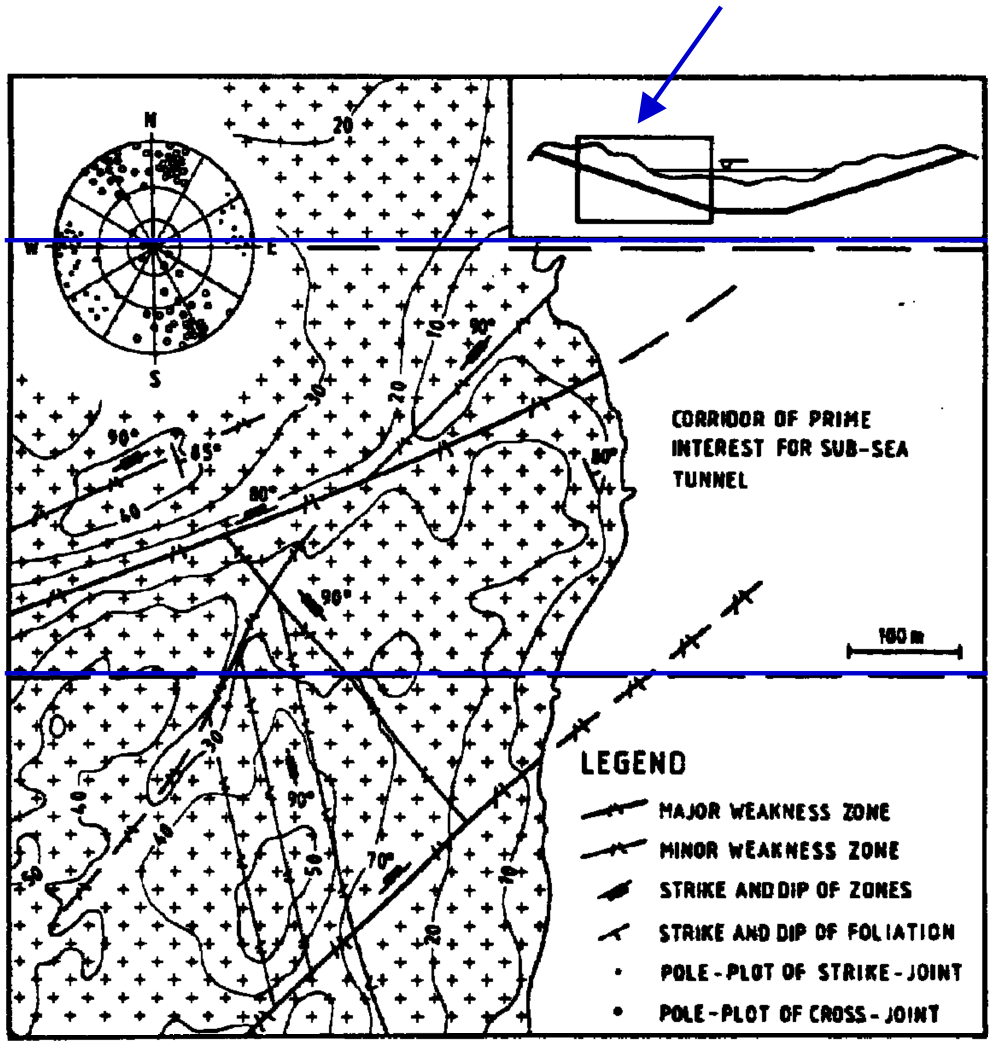
3) OFF SHORE ACOUSTICAL PROFILING

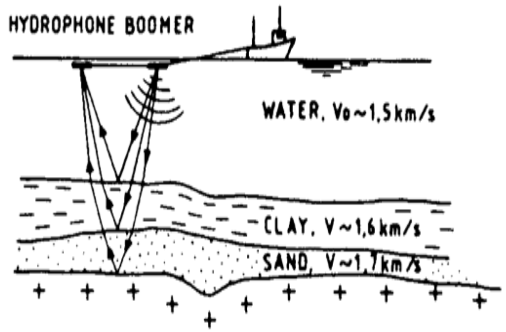
4) OFF SHORE REFRACTION SEISMIC PROFILING

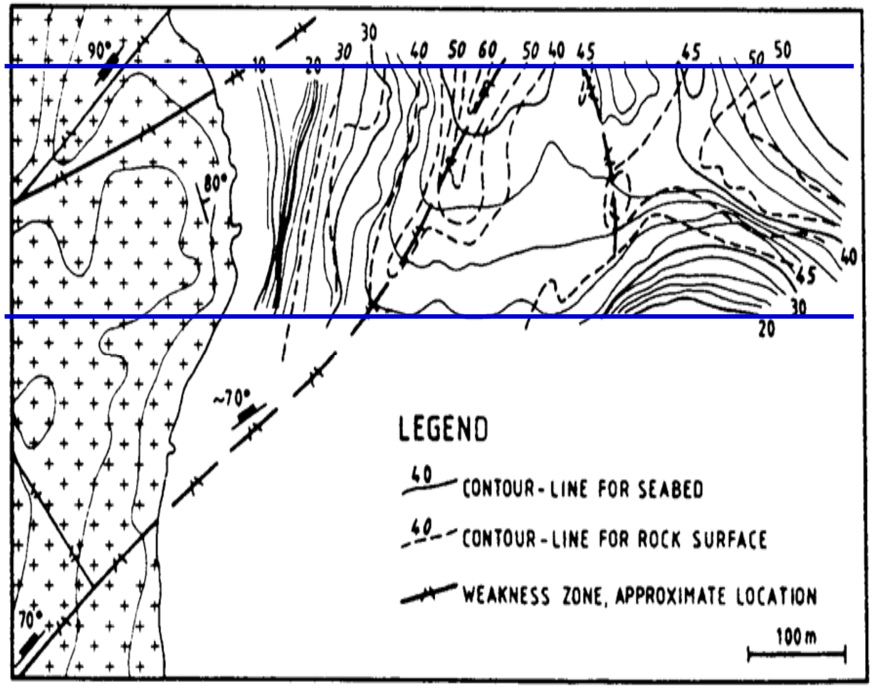
5) DRILLING

STEP 1 - DESK STUDY
STEP 2: FIELD MAPPING

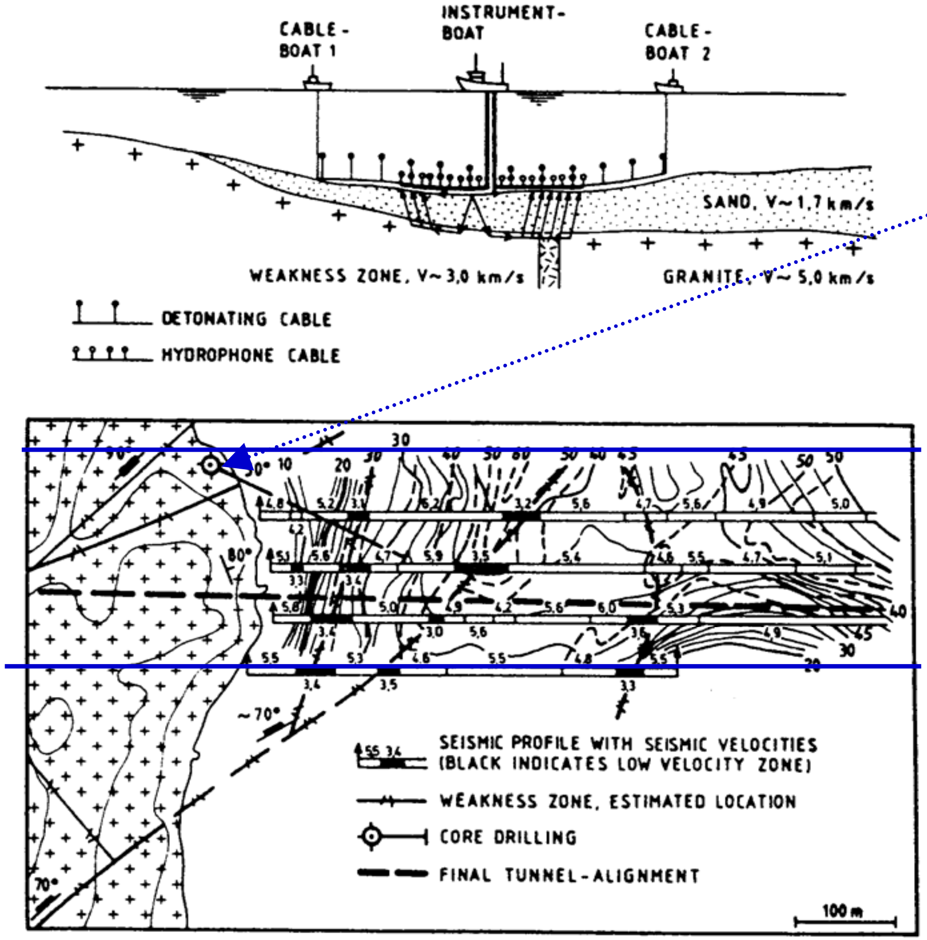
STEP 3 - ACOUSTICAL PROFILING



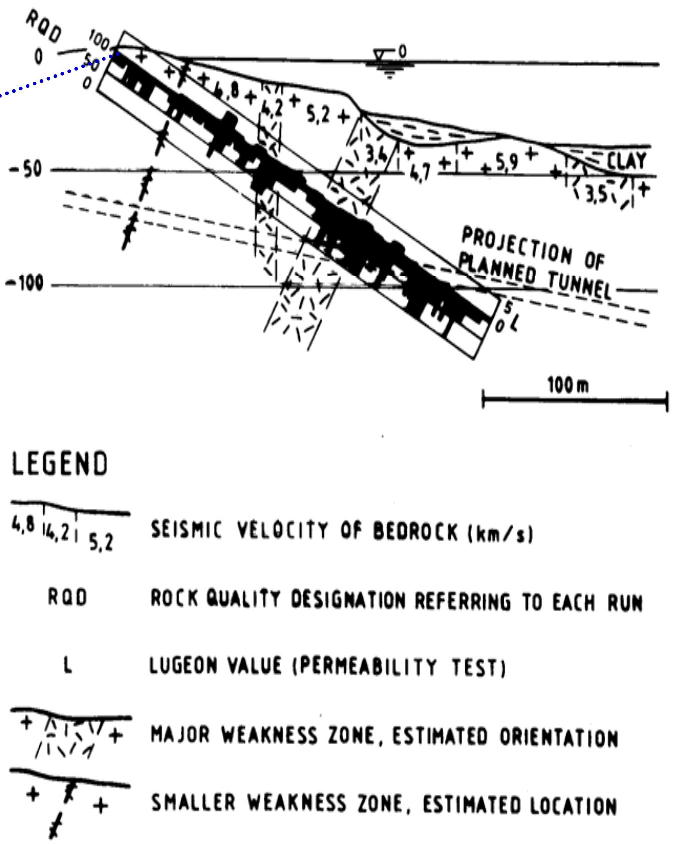




STEP 4 - REFRACTION SEISMIC PROFILING



STEP 5 - DRILLING



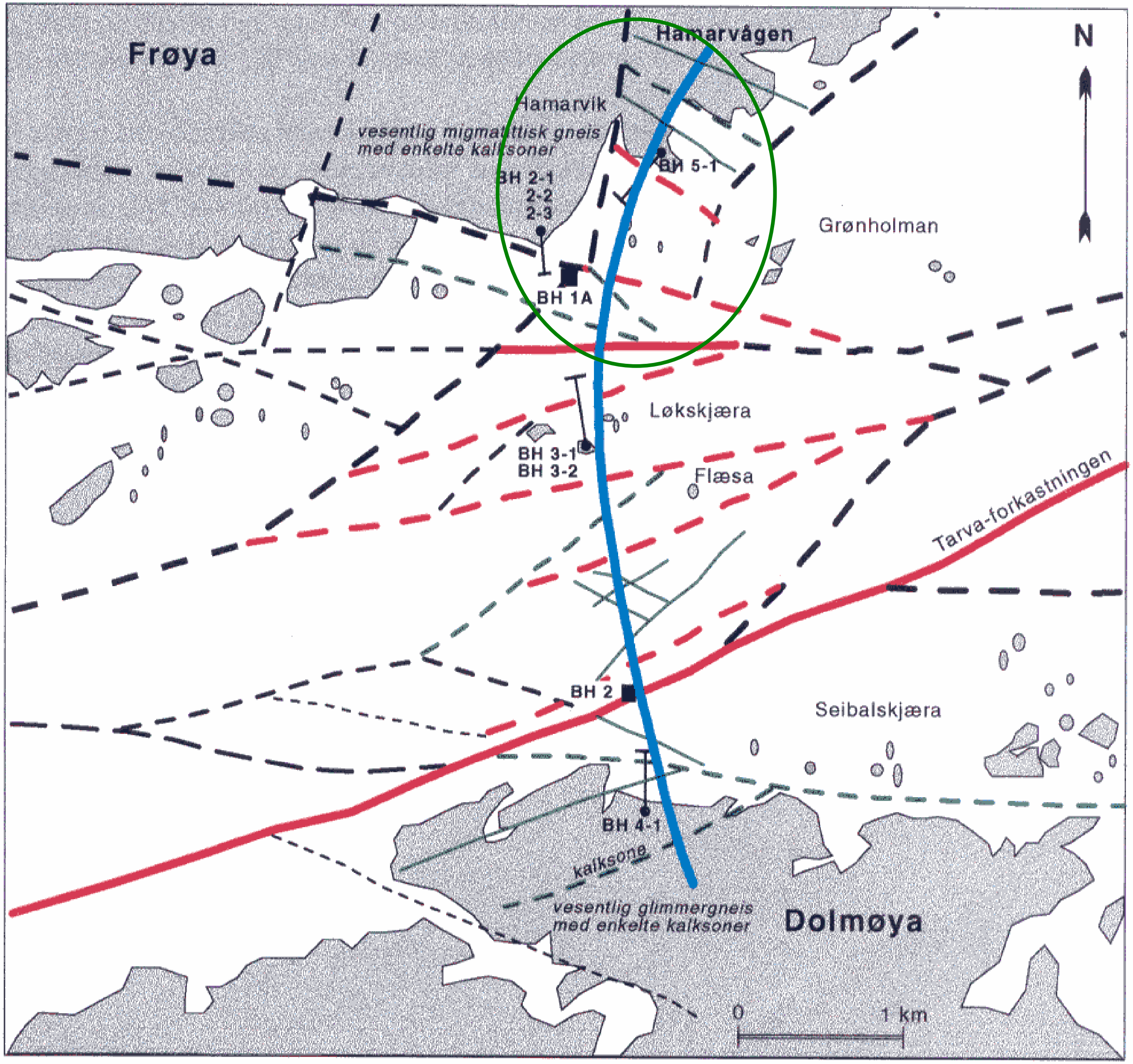
GEO-INVESTIGATION PRIOR TO EXCAVATION

TYPICAL EXTENT FOR NORWEGIAN SUB SEA TUNNELS:
5-10% OF EXCAVATION COST

IN MOST CASES PRE-CONSTRUCTION INVESTIGATIONS GIVE A GOOD BASIS FOR PLANNING AND CONSTRUCTION
EXAMPLE: FRØYA

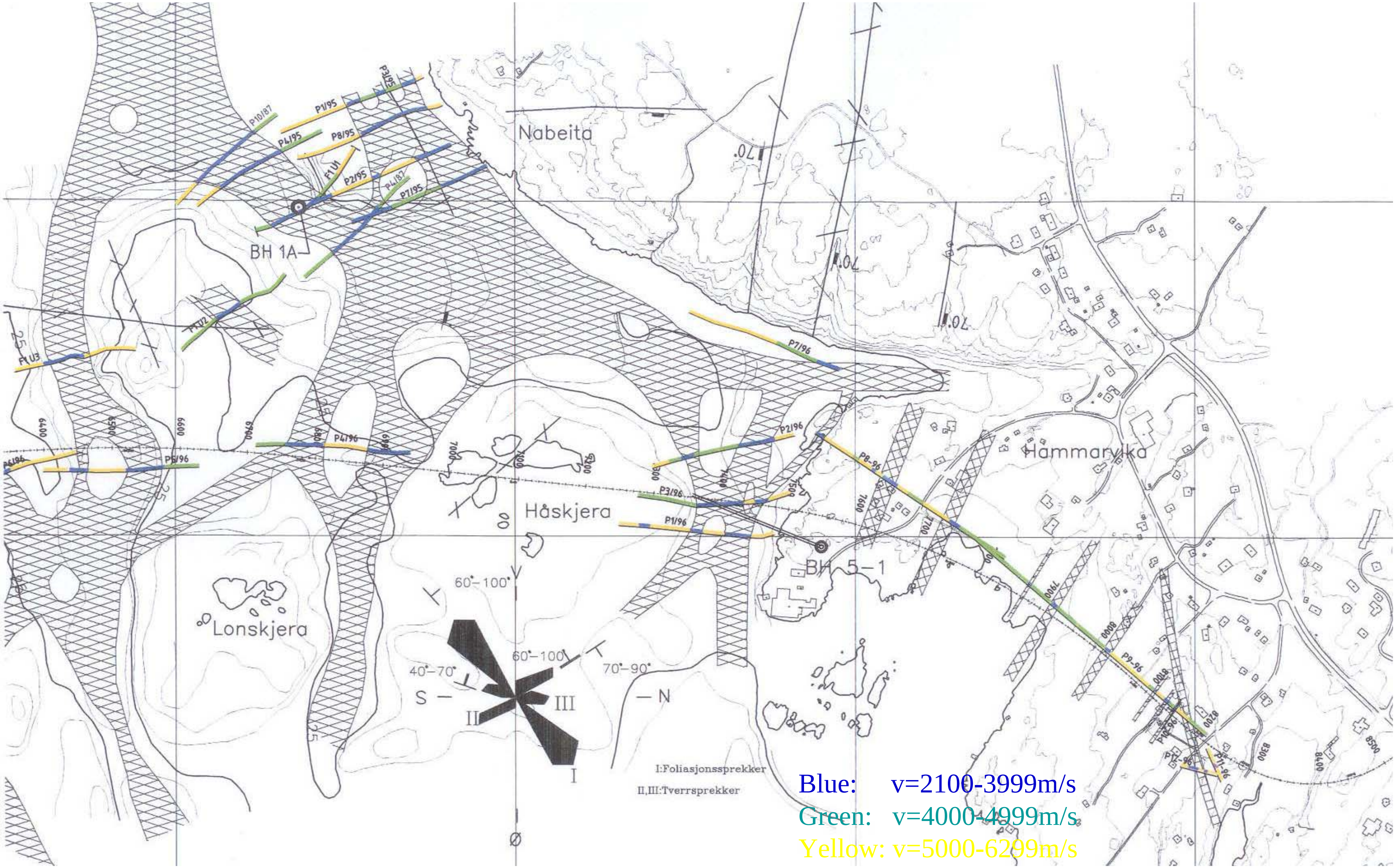
IN SOME CASES UNEXPECTED CONDITIONS ENCOUNTERED IN SPITE OF EXTENSIVE INVESTIGATIONS
EXAMPLE: OSLOFJORD

FRØYA SUB SEA ROAD TUNNEL (2000)

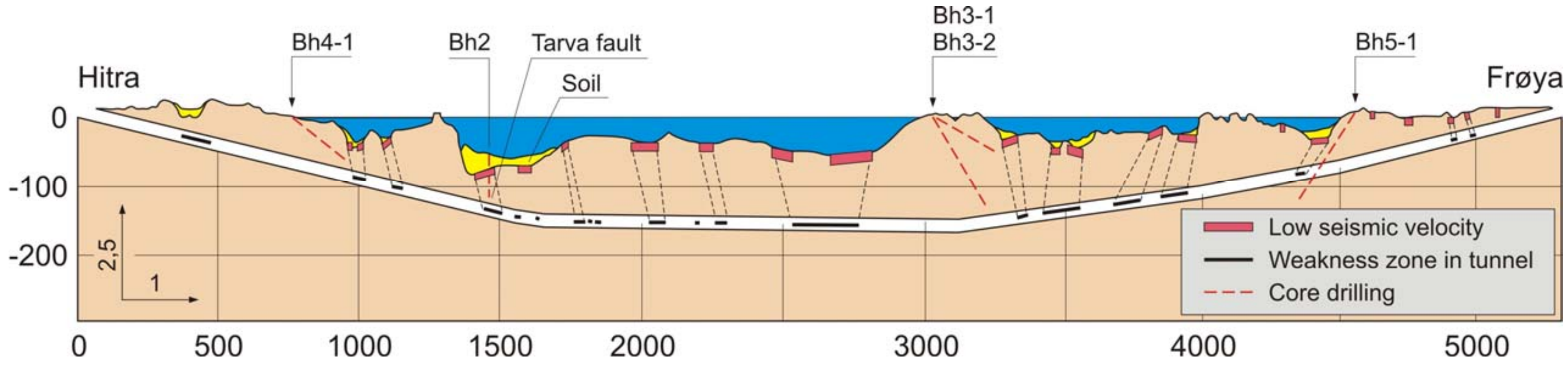


5.2 km / 164 m.b.s.l.

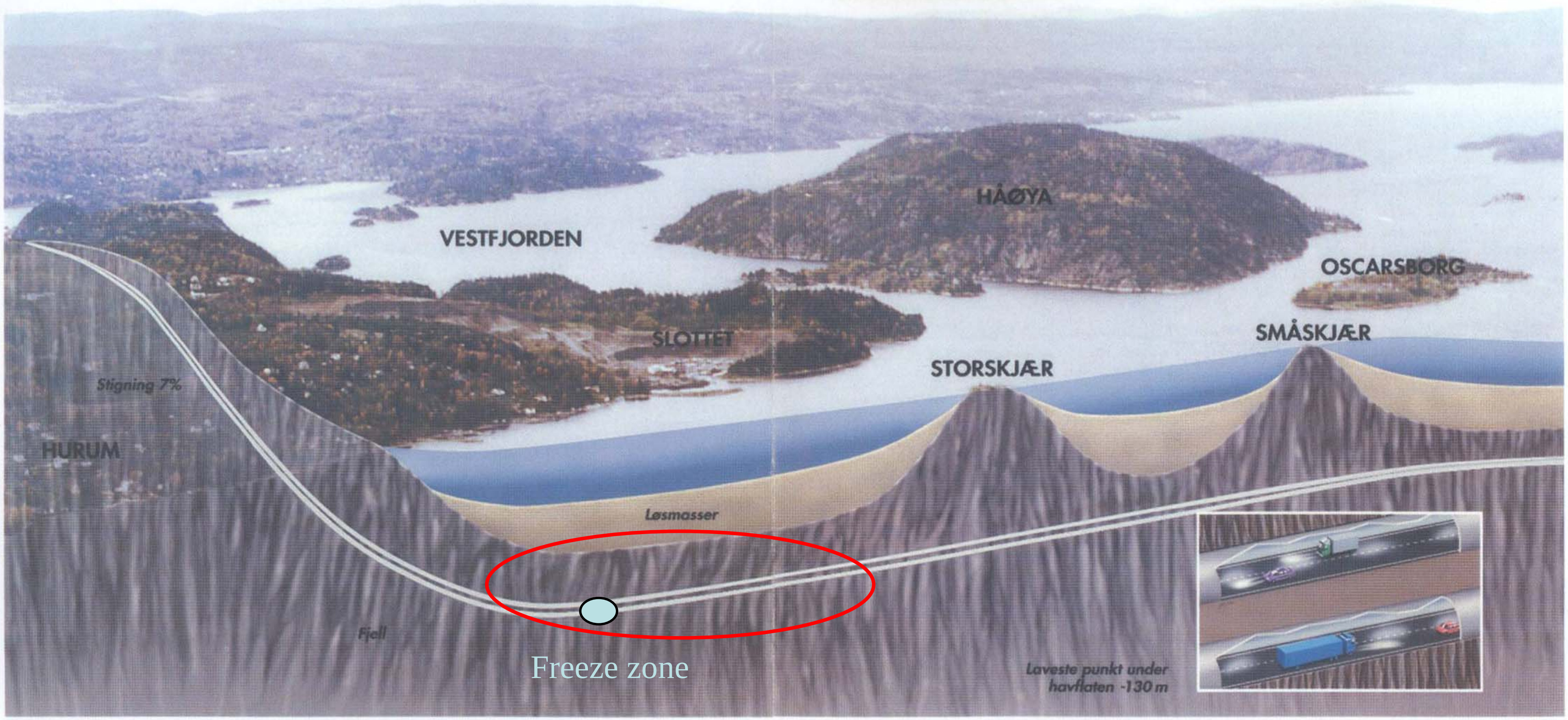
INVESTIGATION RESULTS, FRØYA TUNNEL - NORTH PART



FRØYA TUNNEL – INVESTIGATION RESULTS vs AS-BUILT



OSLOFJORD SUB SEA ROAD TUNNEL



Oslofjordforbindelsen er en ferjefri kryssing av Oslofjorden mellom E6 i Frogn og E18 ved Lier/Drammen. Forbindelsen vil føre til en betydelig bedret infrastruktur i Østlandsregionen, og ha stor trafikk- og miljømessig betydning for vegnettet i hele området.

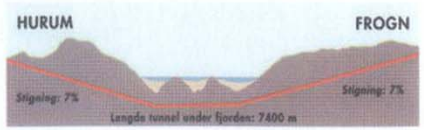
Gjennom bygging av Oslofjordforbindelsen åpnes en ny hovedkorridor for nærings-utvikling sør for Oslo. Den knytter områdene øst og vest for fjorden sammen, skaper raskere kommunikasjoner mot Sverige og kontinentet, og avlaster de sentrale deler av Oslo - området ved å åpne nye områder for utbygging.

Oslofjordforbindelsen er planlagt bygd ut som en 7,4 km lang fjelltunnel under fjorden. Når den står ferdig vil den bli verdens lengste undersjøiske vegtunnel.

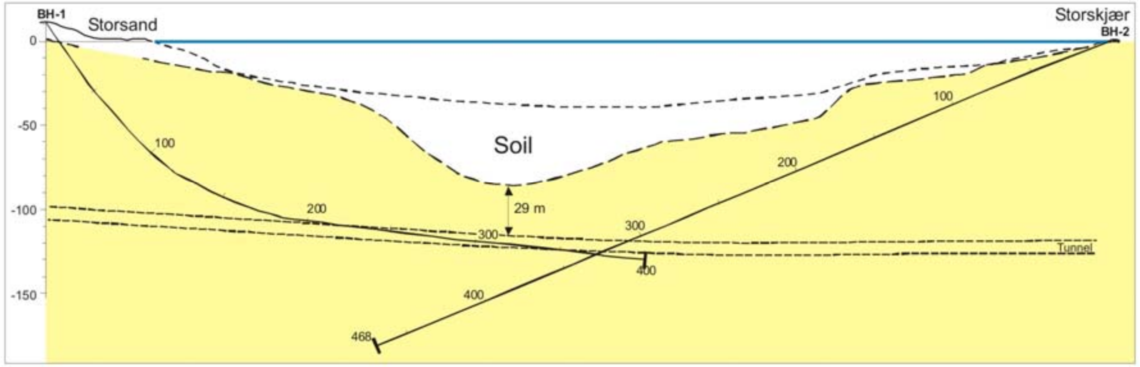
TEKNISKE DATA

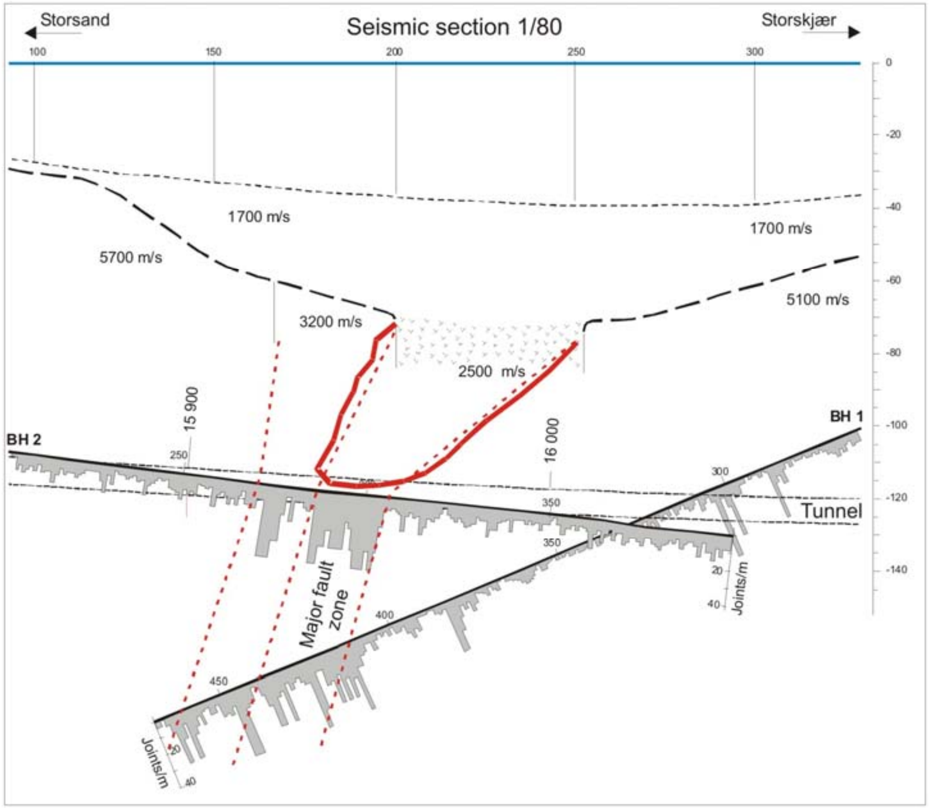
Total lengde:	26,9 km
- av dette utgjør tunneler:	9,8 km, eller ca.36 % av lengden
- og bruer:	830 m
Vegbredde:	10 m
Oslofjordtunnelens lengde:	7400 m
Største stigning:	7 %
Laveste punkt under havflaten:	-130 m
Tverrsnitt:	2 tunnelløp, hvert med 2 kjørefelt.

Byggekostnad:	1.270 mill.kr.(1994)
- herav Oslofjordtunnelen:	655 mill.kr.
Byggetid Oslofjordtunnelen:	ca. 3 år
Byggetid veger på land:	ca. 2 år



ERODED CHANNEL, OSLOFJORD SUB SEA ROAD TUNNEL





UNCERTAINTY AND RISK REGARDING GROUND CONDITIONS

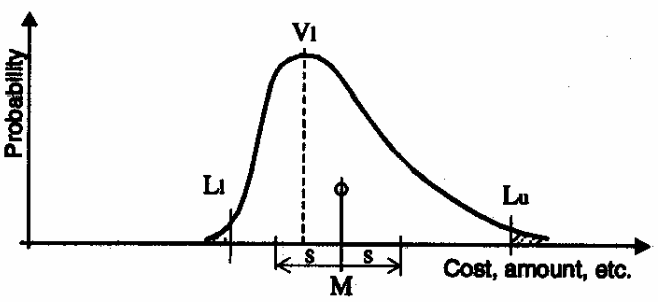
EVEN VERY EXTENSIVE GROUND INVESTIGATIONS MAY NOT UNCOVER ALL FEATURES OF THE ROCK MASS
=>
UNEXPECTED CONDITIONS MAY ALWAYS BE ENCOUNTERED -
BUT THE RISK MAY BE SIGNIFICANTLY REDUCED BY:

- ADJUSTING THE EXTENT OF INVESTIGATION TO THE GEOLOGICAL COMPLEXITY AND TYPE OF PROJECT
- ENSURING FULL UNDERSTANDING OF GEOLOGY AND TECTONICS
- NOT BASING INVESTIGATIONS ON BIDDING
- CONTINUOUS INVESTIGATION THROUGH THE ENTIRE CONSTRUCTION PERIOD
- INCLUDING RISK AND UNCERTAINTY ANALYSES IN THE PLANNING PROCESS
- USING INDEPENDENT REFERENCE PANELS FOR QUALITY CONTROL AND ASSURANCE OF COMPLEX PROJECTS

UNCERTAINTY ANALYSIS BASED ON LICHTENBERG's METHOD

Table 2 Uncertainty analysis ("max/min-estimation") based on Lichtenberg's method.

CLASS		UNIT	Ll	Vl	Lu	M	M (NOK)	s	s (NOK)	s^2 (NOK)
GROUND QUALITY	1	m	700	1235	2000	1 281		260	2 162 472	4,67629E+12
		NOK/m	7000	8362	9500	8 317	10 654 333	500	640 500	4,1024E+11
	2	lm	1200	1720	2500	1 772		260	2 611 492	6,81989E+12
		NOK/m	8400	10107	11500	10 044	17 798 322	620	1 098 640	1,20701E+12
	3	m	600	1060	1700	1 096		220	2 913 416	8,48799E+12
		NOK/m	11000	13338	15200	13 243	14 514 109	840	920 640	8,47578E+11
	4	m	50	330	500	308		90	1 658 430	2,75039E+12
		NOK/m	14500	18545	22000	18 427	5 675 516	1 500	462 000	2,13444E+11
	A	m	50	125	300	145		50	868 110	7,53615E+11
		NOK/m	13500	17437	21000	17 362	2 517 519	1 500	217 500	47306250000
	B	m	150	240	400	254		50	2 443 710	5,97172E+12
		NOK/m	39000	48457	60000	48 874	12 414 047	4 200	1 066 800	1,13806E+12
	C	m	150	380	600	378		90	6 749 190	4,55516E+13
		NOK/m	56000	73985	97000	74 991	28 346 598	8 200	3 099 600	9,60752E+12
	D	m	10	140	280	142		54	8 862 869	7,85504E+13
		NOK/m	135000	155212	220000	164 127	23 306 062	17 000	2 414 000	5,8274E+12
FREEZING		m	0	0	50	10		10	3 100 000	9,61E+12
		NOK/m	250000	300000	400000	310 000	3 100 000	30 000	300 000	90000000000
PROBE DRILLING	I	m	3500	4310	4500	4 186		200	32 400	1049760000
		NOK/m	150	160	180	162	678 132	6	25 116	630813456
	II	m	250	320	1000	442		150	41 430	1716444900
		NOK/m	240	267	340	276	122 080	20	8 840	78145600
	III	m	300	600	1100	640		160	208 032	43277313024
		NOK/m	1000	1167	2000	1 300	832 128	200	128 000	16384000000
PRE-GROUTING	i	m	400	1195	3200	1 437		560	4 095 168	1,67704E+13
		NOK/m	5000	7188	10000	7 313	10 508 494	1 000	1 437 000	2,06497E+12
	ii	m	300	745	1500	807		240	5 140 464	2,64244E+13
		NOK/m	15000	19031	35000	21 419	17 284 810	4 000	3 228 000	1,042E+13
	iii	m	10	70	200	84		38	5 283 528	2,79157E+13
		NOK/m	60000	145067	200000	139 040	11 679 377	28 000	2 352 000	5,5319E+12
						SUM =	159 431 528		$(\Sigma S^2)^{0.5}$ =	16 484 868



$V_l = 1/5(L_l + 3V_l + L_u)$

$s = 1/5(L_u - L_l)$