Is TBM a feasible and viable tunneling method for deep subsea tunnels?

A 'Speed Date' on considerations on TBM for Rogfast sub sea road tunnel & Oil tunnels in North Sea

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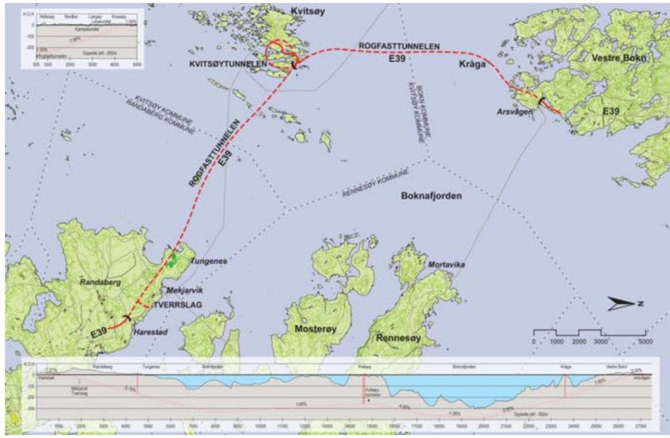
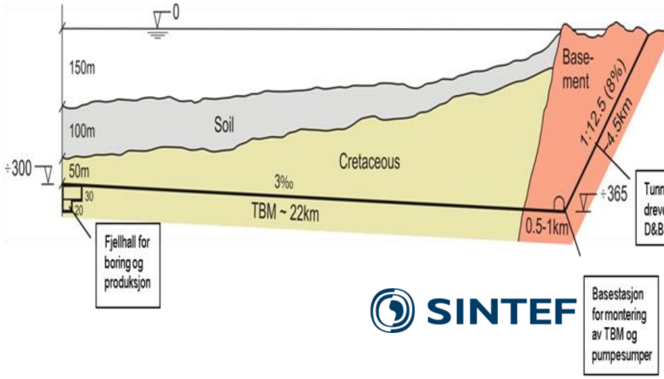
TBM APPLICATION III - introduction



Some points on the presented examples:

- They are initial tests on TBM-application for this kind of projects and circumstances
- There are no merits on similar projects and concepts
- These are theoretical approaches for concept tests
- Challenging TBM-application in an 'out of the box' thinking and squeezing it to the edge of tehnology
- Could a TBM give value added to the Rogfast project with respect to feasibility and do-ability?
- Would 3 TBM's have sufficient robustness for 20-30-40 km long tubes and compete in cost and time?



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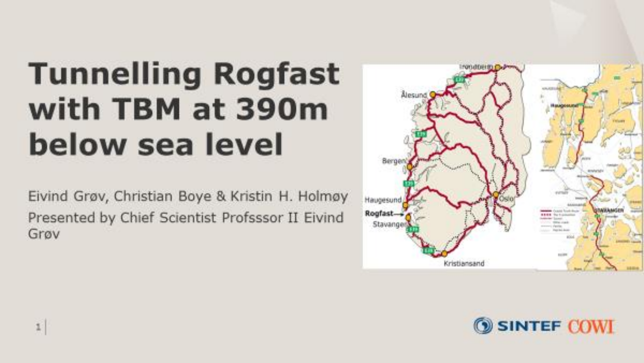
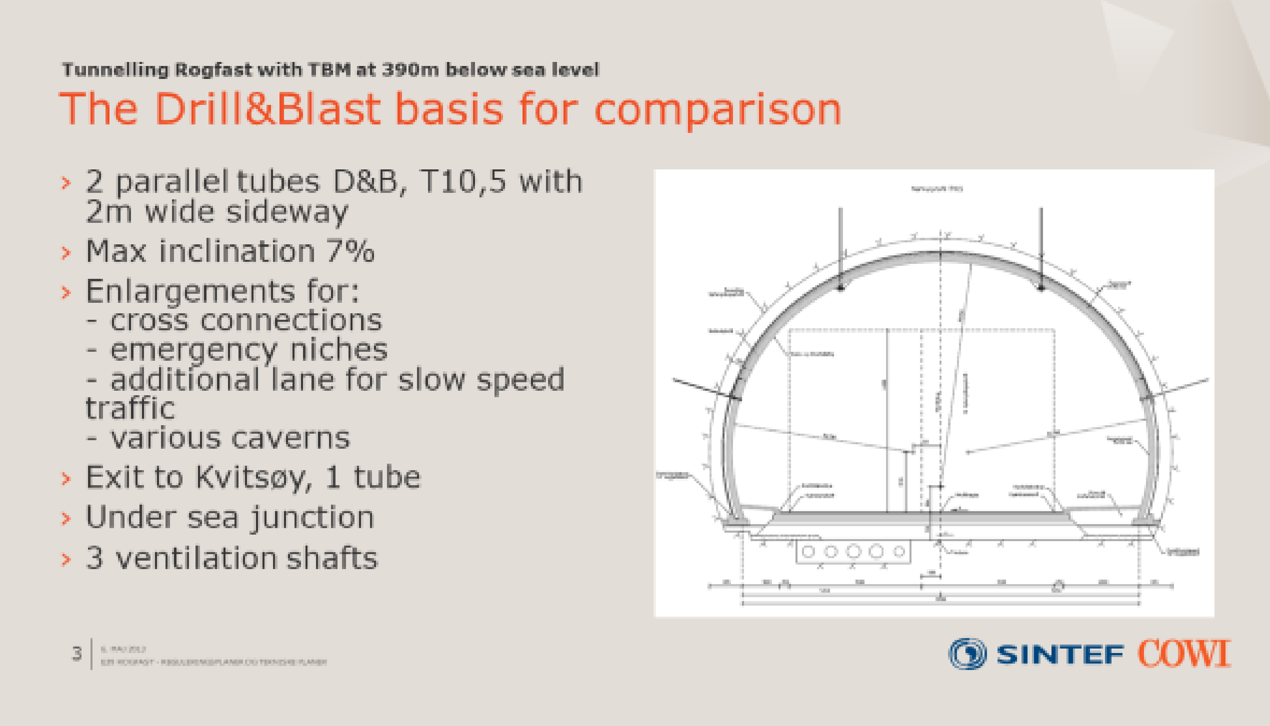
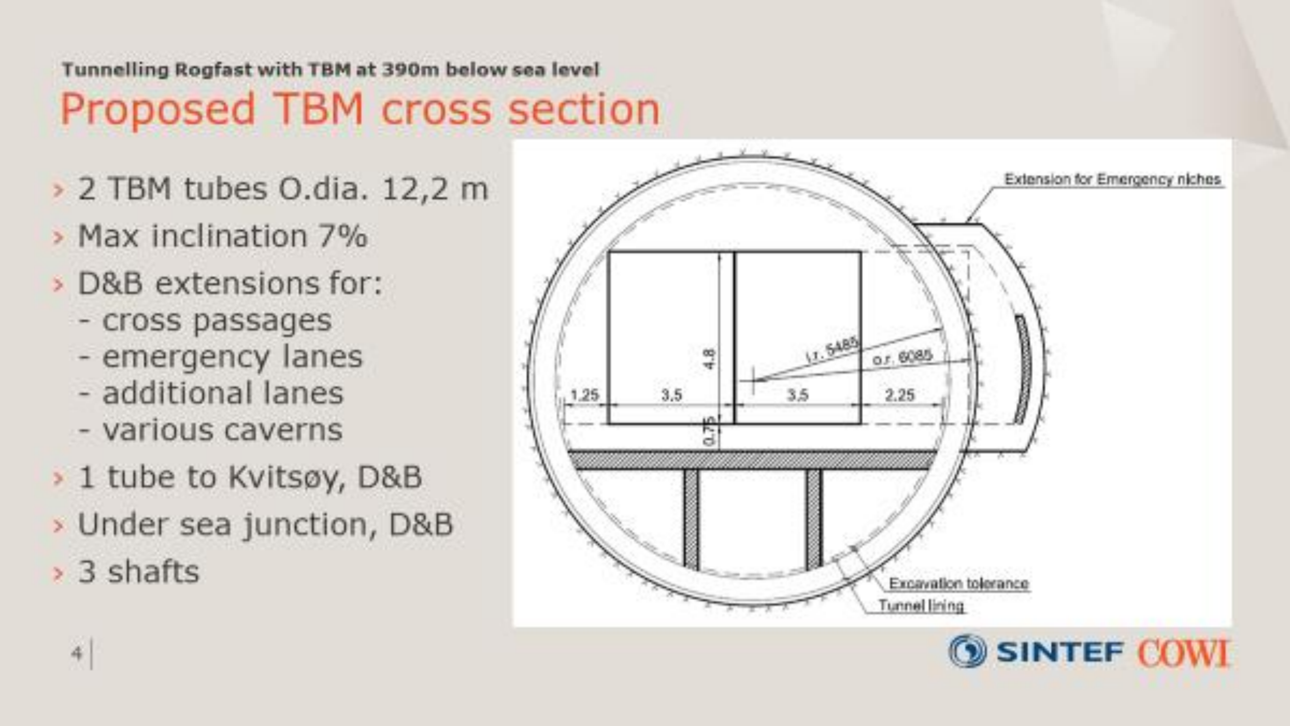
- COWI & SINTEF prepared feasibility study for Rogast and included a concept test using TBM
- Presented at 2013 Strait Crossing Conference, Bergen
- First thing to do; identify a cross section to fit in dual lanes







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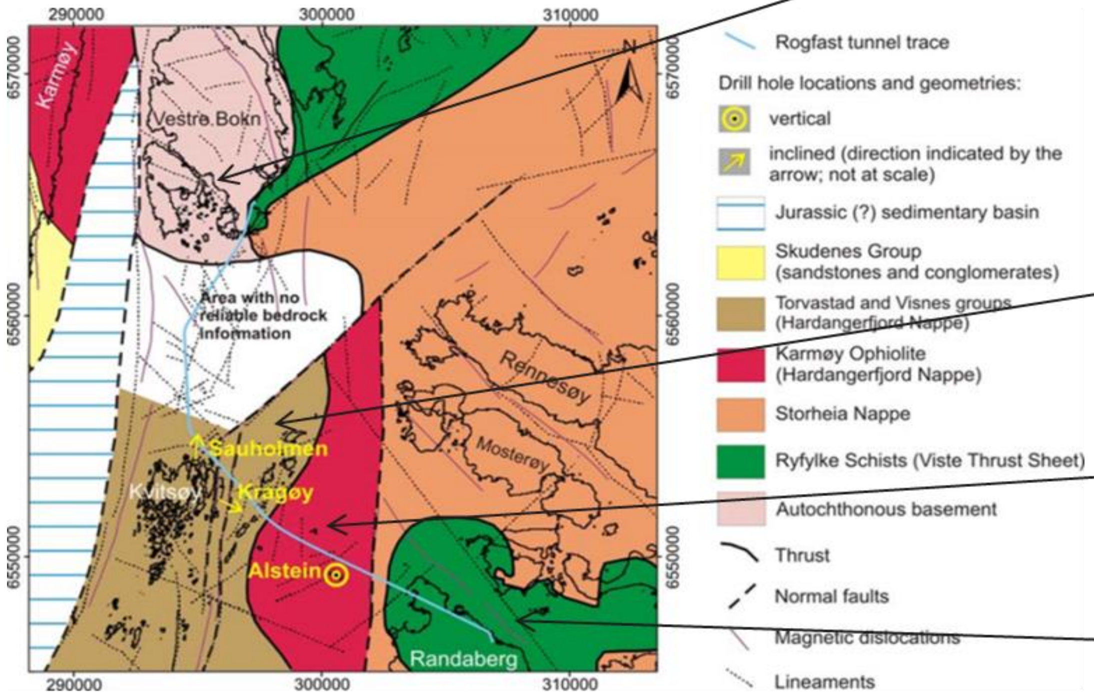


Granitic to dioritic gneissic basement

8%

18%

Greenstones , pillow- and breccia-lavas, tuffs, quartz-rich black shales, diabase dykes, etc

51%

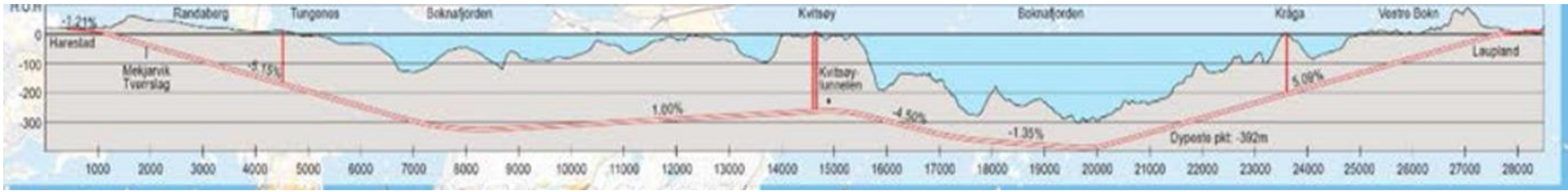
Lower Ordovician intrusive mafic and ultra-mafic rocks, gabbro

23%

Amphibolites, phylites and mica schists

A brief geological overview of the tunnel area

Geological conditions én route based on information in 2012



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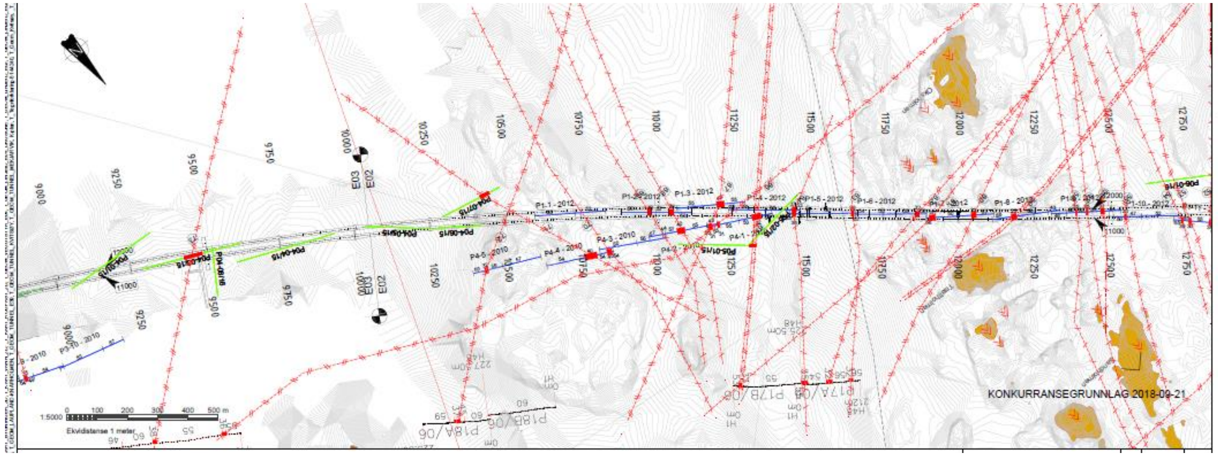
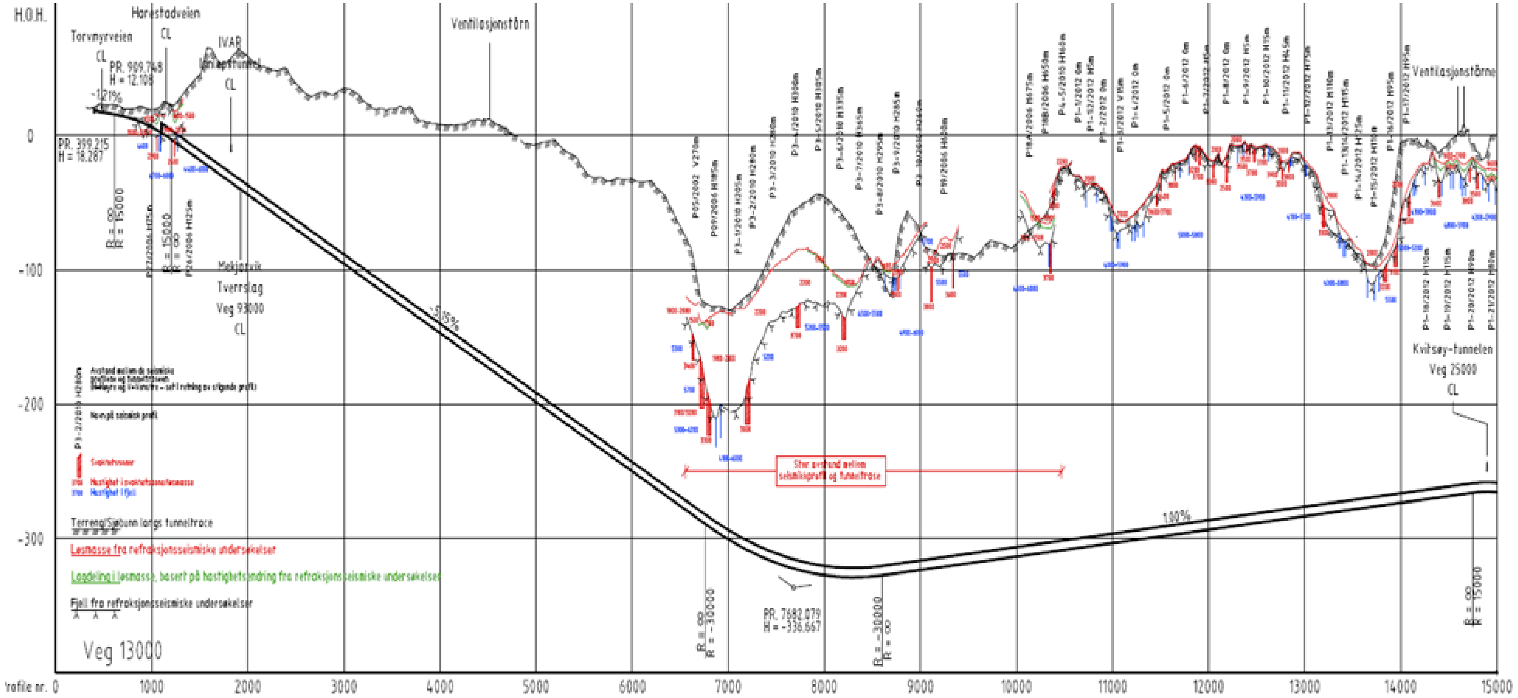
First part of tunnelling from the Stavanger side is pretty much a walk in the park – well known geology



Critical points:

- Harestad, shortly after access, at profile 1250, topo shows 10mcover
- Tungenes fault, at profile 6700, rock cover is appr. 60-65m
- Shear zone next to Kvitsøy, at profile 13900



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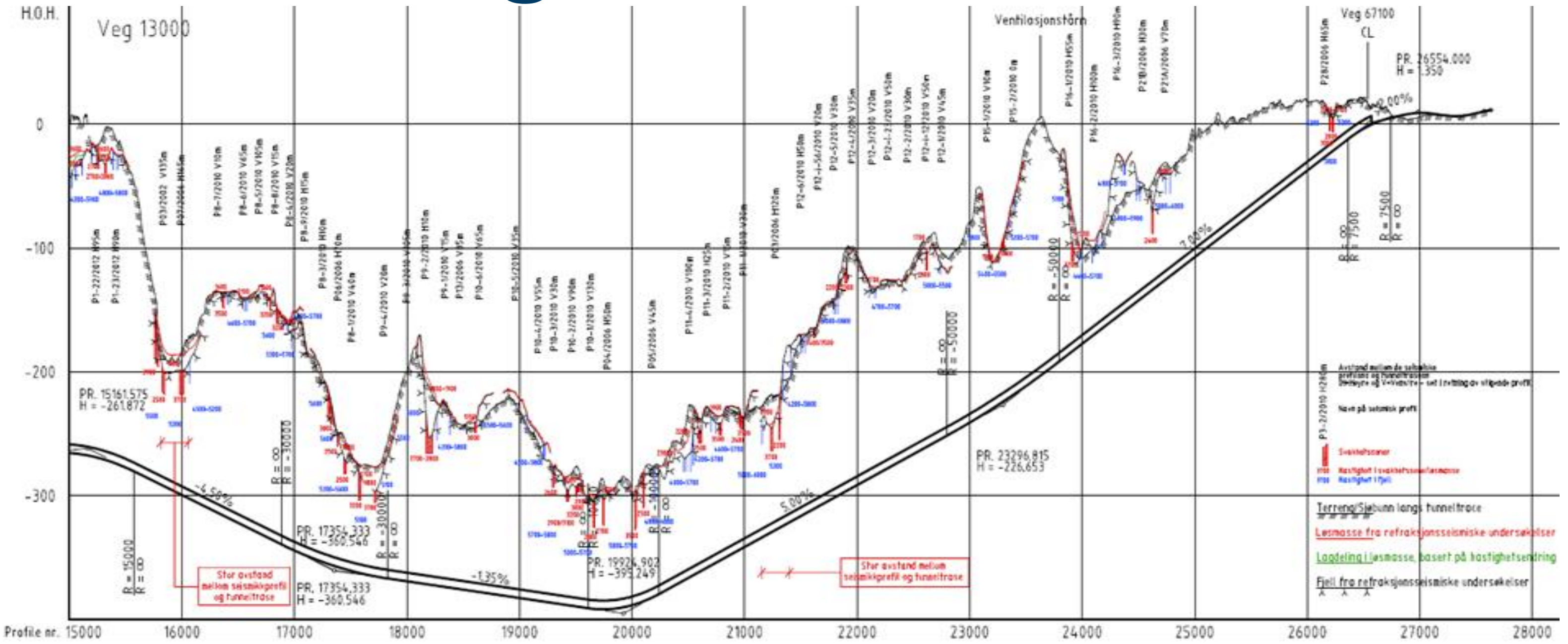
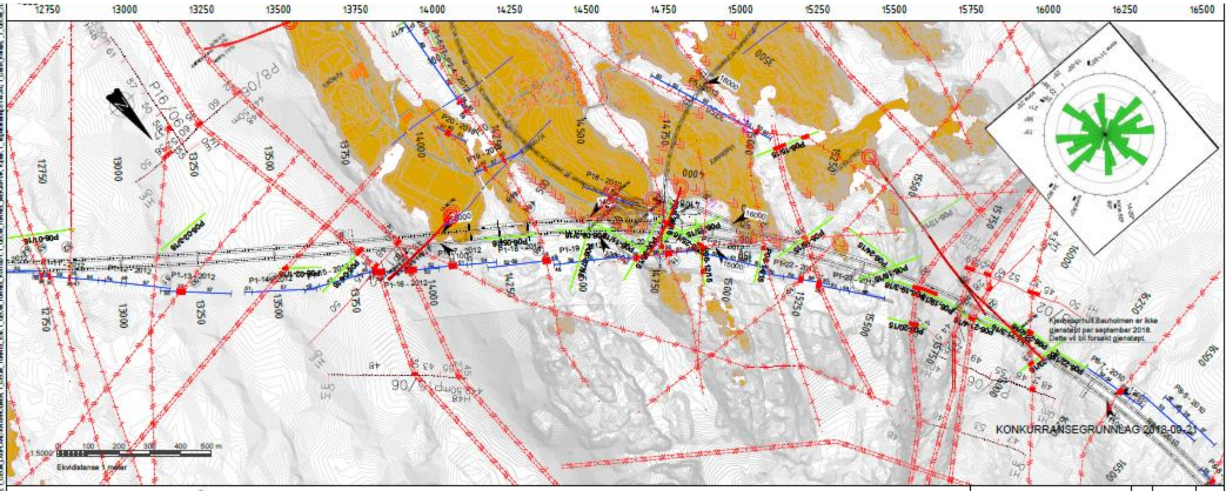
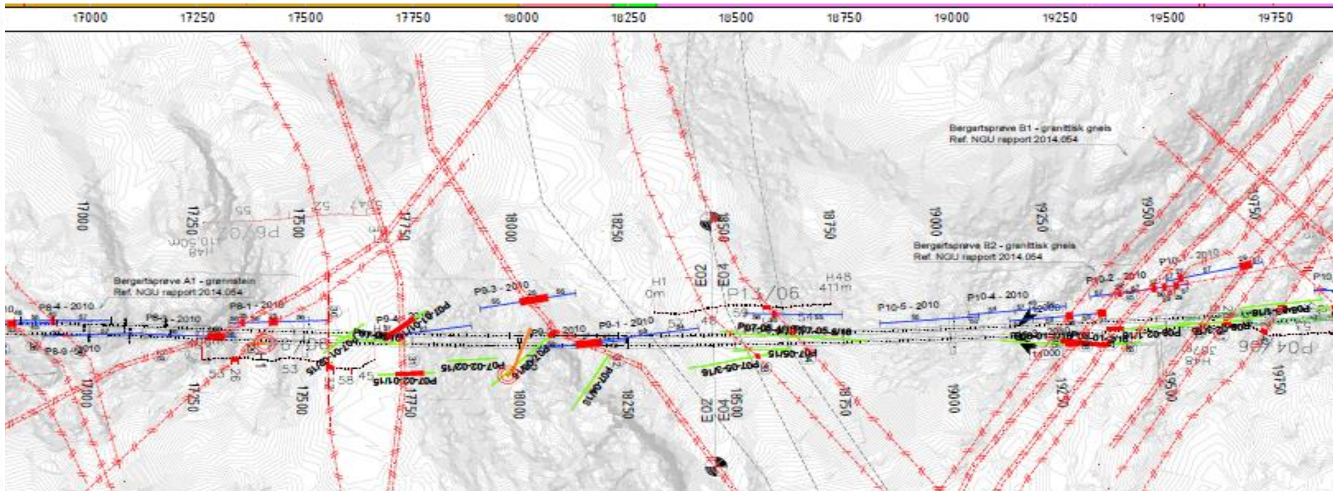
- Weakness zone (Fault) noprth of Kvitsøy, at profile 15750-15850, described in core hole drilled from a isle
- At profile 17400-17750, rock cover appr. 60m, soil thickness 20m
- Next to the aproach North, profile 23490-24630, rock cover 55 to 60m
- Several lineaments in this section







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Geological conditions

Seismic velocity (m/s)%	Q-value	Length along tunnel trace (m)		Share in %		
		Section with seismic profiles	For the entire tunnel	Section with seismic profiles	For the entire tunnel	
5500-6000	10-40 : Good	3 950	5 020	24.2	19.7	20%
5000-5500	4-10 :Fair	8 430	14 740	51.6	58.0	58%
4500-5000	1-4 : Poor	1 530	3 000	9.4	11.8	10%
4000-4500	0.4-1 : V.poor	880	880	5.4	3.5	
4000-3600	0.1-0.4 : V.poor	440	670	2.7	2.6	
3200-3600	0.04-0.1 : E.poor	290	290	1.8	1.1	
2800-3200	0.01-0.04 : E.poor	400	400	2.4	1.6	10%
2500-2800	0.004-0.01 : Exc.poor	270	270	1.7	1.1	
2000-2500	0.001-0.004: Exc.poor	150	150	0.9	0.6	
		16 340	25 420	100	100	

TBM APPLICATION III – Rogfast sub sea tunnel

Expected geological conditions along the tunnel alignment

- Static water pressure up to a maximum of 390 m
- Several weakness zones both S and N of Kvitsøy, up to a width > 60 m.
- Some zones are expected to have Q-values below 0.003.
- Phyllite, greenstone, slate expected favorable rock types for TBM, approx. 40%
- Grouting is expected in (meta)gabbro and gneiss, approx. 40%
- Variation in rock mass quality may occur over short distances.
- 83 zones of poor rock mass quality (Q <1), length of 2660 m = 10 % of length
- 42 of the 83 zones have estimated Q-value between 0.1 and 1, total 1550 m
- 41 of the 83 zones have estimated Q-value below 0.1, total 1110 m
- Swelling clay expected in weakness zones, 0.28 MPa = moderately active clay
- May have low in-situ stress levels causing a risk of major leakage
- Regional faults where the distal part may be water-bearing

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How to meet these challenges with a TBM?

- TBM to be equipped to perform various activities that enables a safe tunnelling process: like probe drilling, pre-grouting and rock support
- Rock mass grouting is 'first line of defense'
- To reduce the risk of instability at tunnel face the possibility to pressurize the face is beneficial, that is EPB-capability - a redundancy measure
- A TBM with possibility of installing concrete segmental lining will provide an additional safety measure whilst traversing weakness zones or certain section of the tunnel and thus ensure a successful project
- Concluded that for this project a so-called "Dual-mode-TBM" with double shield and EPB-capacity is recommended

➡ Created a set of performance criterion for the project

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A. Probe drilling ahead of tunnel face with different configurations of length, direction up to 50 m, and collaring within and outside the tunnel contour with 360 degree coverage. Probe holes upward for control of rock cover.
B. Core drilling in front of the tunnel face to reach a capacity up to 200 m in length.
C. Drill holes for grouting ahead of the tunnel face with length up to 25m coverage as probing. Grout ahead of tunnel face with equipment able to work simultaneously with three parallel injection lines
D. Park the TBM face in EPB mode (closed front) with back pressure of 15 bar, and to operate within closed mode up to 10 bar. Such technology may be developed to handle higher water pressure heads in the future. Cutter head to be sealed to reduce the possibility that poor rock or water flushes through the head.
E. Switch quickly, efficiently between construction with and without concrete segments. Support to be applied behind the TBM shield applying bolts and shotcrete.

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F. In such as phyllite and slate it is expected to run without concrete segmental lining as in 'Open-beam' mode.

G. Behind the TBM shield the rock mass will be supported using conventional methods such as rock bolts and sprayed concrete.

H. Collect, store and systemize all such data as including trust, power consumption, RPM and gross progress in 'real time' etc.

I. Drain the face to keep water pressure acting at the tunnel below predefined values.

J. Install adequate pumping capacity at the TBM.

K. Cutters to be replaceable behind the cutter head.

L. An air lock to allow manual interventions under compressed air into the cutterhead e.g. for cutter replacement etc. in case this is urgently required in a zone of adverse ground.

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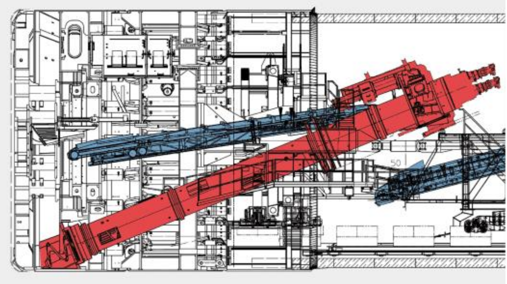
Choice of TBM – A dual mode TBM

- Mixshield-TBM or dual-mode TBM having combined capacities of an EPB-TBM and a single/double shield TBM
- Capable of switching boring mode during the tunnel excavation
- Being suited for rock mass conditions that vary from good & hard rock to weak & unstable water infected rock mass
- Dual-mode TBM that will be equipped with dual transport systems from the tunnel face and backwards – screw and conveyor
- This solution provides the best of technologies from various TBM-types, it increases cost but secures reliability and accomplishment - mucking out by conveyor belt - conventionally



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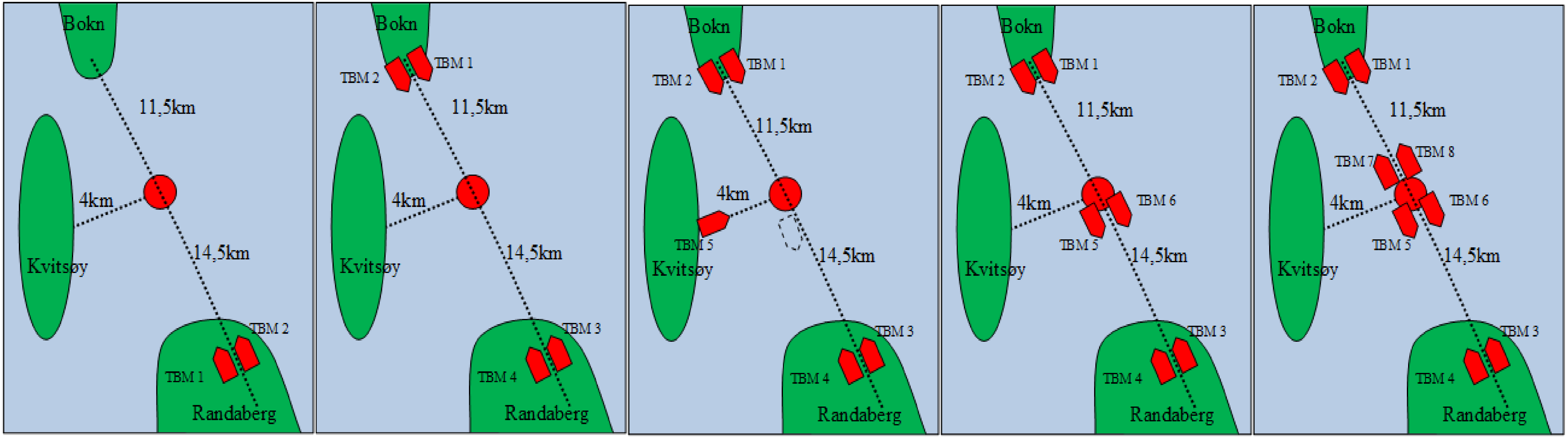
A variety of combinations of number of TBMs



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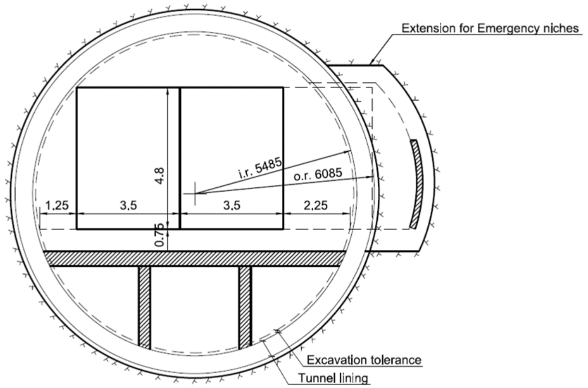
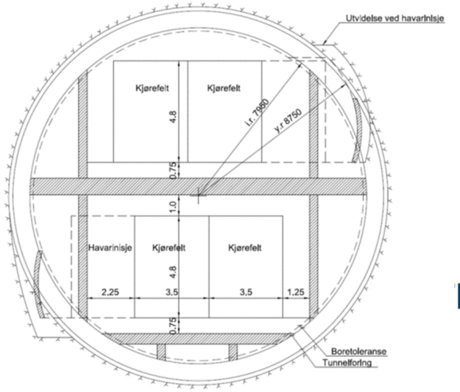
Evaluation of TBM Combinations

		TBM cost	Construction time	Performance & logistics	Flexibility
DUAL LANE					
2 TBMs		☺☺☺☺☺	☹	☺☺☺	☹
4 TBMs		☺☺☺☺	☺☺	☺☺☺	☺☺
5 TBMs		☺☺☺	☺☺😐	☺☺	☺☺☺
6 TBMs		☺☺	☺☺☺	☺	☺☺☺☺
8 TBMs		☹	☺☺☺☺	☹	☺☺☺☺☺
DOUBLE DECK OPTION					
		TBM cost	**Construction time**	**Performance & logistics**	**Flexibility**
1 TBM		☺☺☺☺	☹	☺☺☺	☹
2 TBMs		☺☺	☺	☺☺☺	☺
4 TBMs		☺	☺☺☺	☹☹	☺☺

Scale: ☹ - poor ->
☺☺☺☺☺- very good





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Excavation risk assessment concluded:

- TBM is fit to deal with changes in geological conditions when identified and recognized as weakness zones early on - as in such cases segmental lining can be planned and installed prior to entering zones
- In unexpected weakness zones such lining may not be installed and the TBM is not prepared for handling the situation. The shield itself will provide some precaution – quite similar to an open D&B tunnel face but more steel to move.
- However, an un-controlled cave-in or water ingress may cause more severe consequences when TBM-tunnelling compared to D&B, risk to damage TBM or even loss of machine.
- Postpone the construction of cross connections until the entire tunnel is completely excavated which allows repair to be done from the neighboring tunnel.

TBM APPLICATION III – Rogfast sub sea tunnel

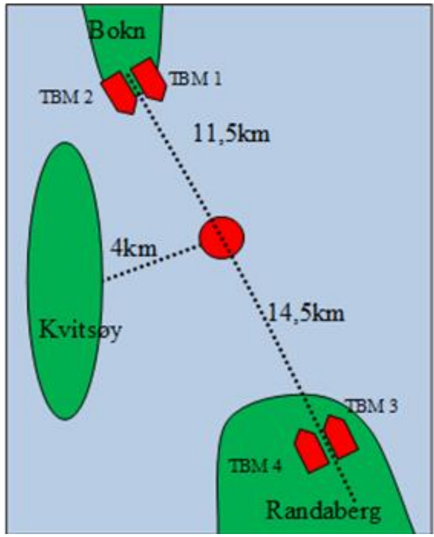
Based on the following scenarios

<u>Scenario 1; 4 TBMs</u>, critical path is 13.8km tunnel,

- average advance rate is 51,8m/week,
- 75m/week in good conditions and
- 13m/week in weakness zones.
- Based on 6 work days per week and 3 shifts á 8 hours. Tunnel to Kvitsøy is not on critical path.

<u>Scenario 2; D&B on 8 tunnel faces simultaneously</u>. Critical path is tunnel to Kvitsøy and then 13,8km on two directions.

- Average advance rate is 27 m/week,
- 34 m/week in good conditions and
- < 10 m/week in weakness zones.
- 6 work days per week and 2 shifts á 10 hours. Added 15% delay due to blasting and other activities on neighboring tunnel faces



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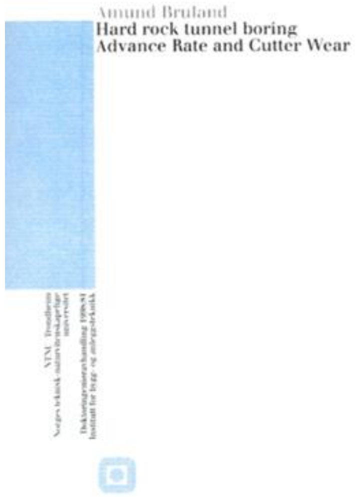
Based on the NTNU prognosis model for D&B and TBM:

- Costs include: excavation, rock support and grouting/probing.
- TBM costs include water&frost protection where segmental lining is not installed.
- Segmental lining in 1/3 of the tunnel length to cover 83 weakness zones, installing lining 30m prior to and 30 m after passing a zone.
- TBM costs include concrete works as presented above.
- D&B costs include full water&frost protection.
- Both cost estimates include capital costs for tunnelling equipment, personnel costs but not costs associated with niches and mobilizing.
- TBM cost is estimated to be 20-35% larger than for D&B option.



→ Difference relates to segmental lining and concrete works

TBM APPLICATION III – Rogfast sub sea tunnel

Construction time estimate

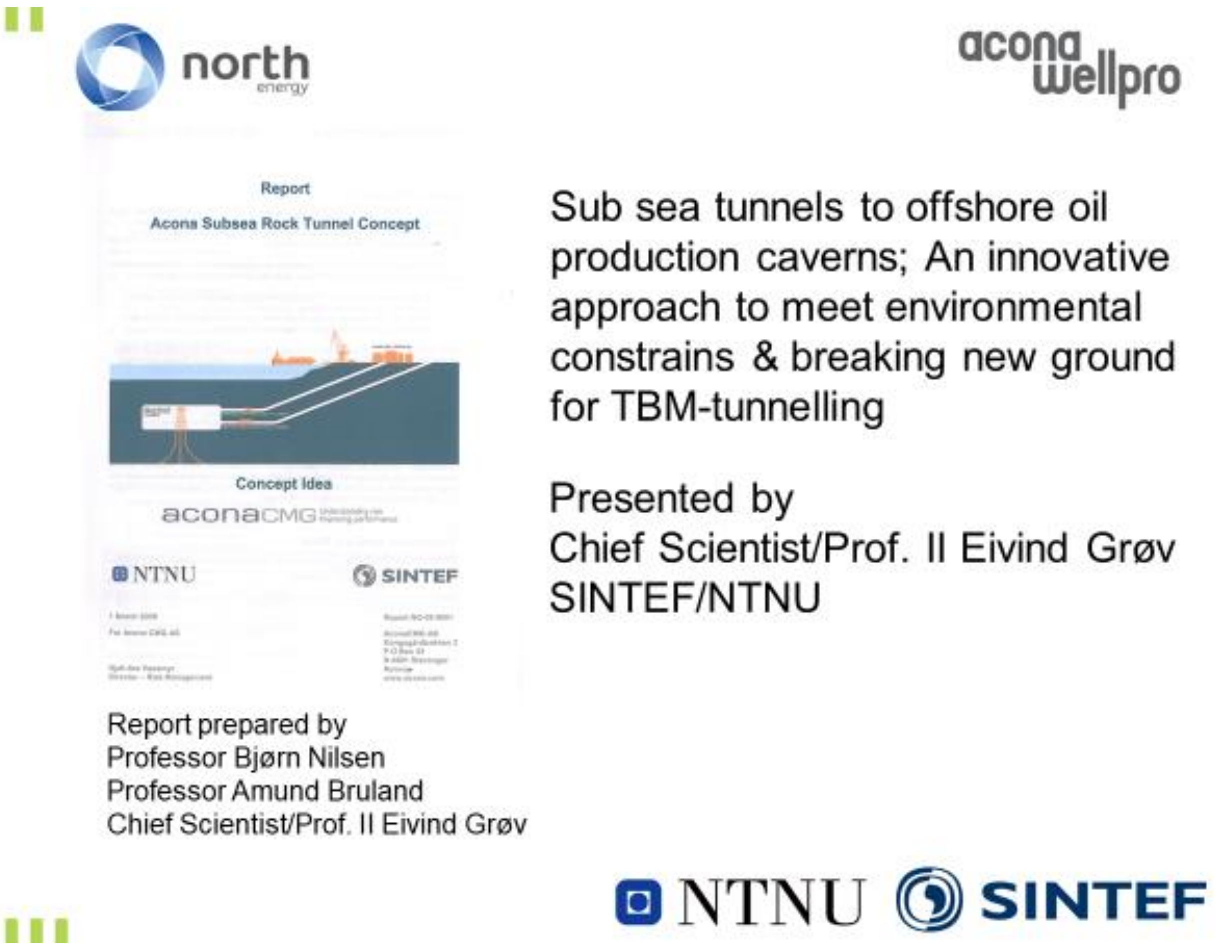
- It is expected that the net excavation time with TBM can be 1,6 years shorter than excavation with conventional drill&blast on 8 tunnel faces.
- This does not include the time needed for procurement, building and delivery, mobilization of the TBM-machines.
- Mobilization for conventional Drill&blast is not included either.
- An overall time schedule for the entire project was not prepared in this study.
- Time estimates do not include niches. Slow traffic lanes, cross connections, tunnel to Kvitsøy etc that need to be excavated but are not on the critical path

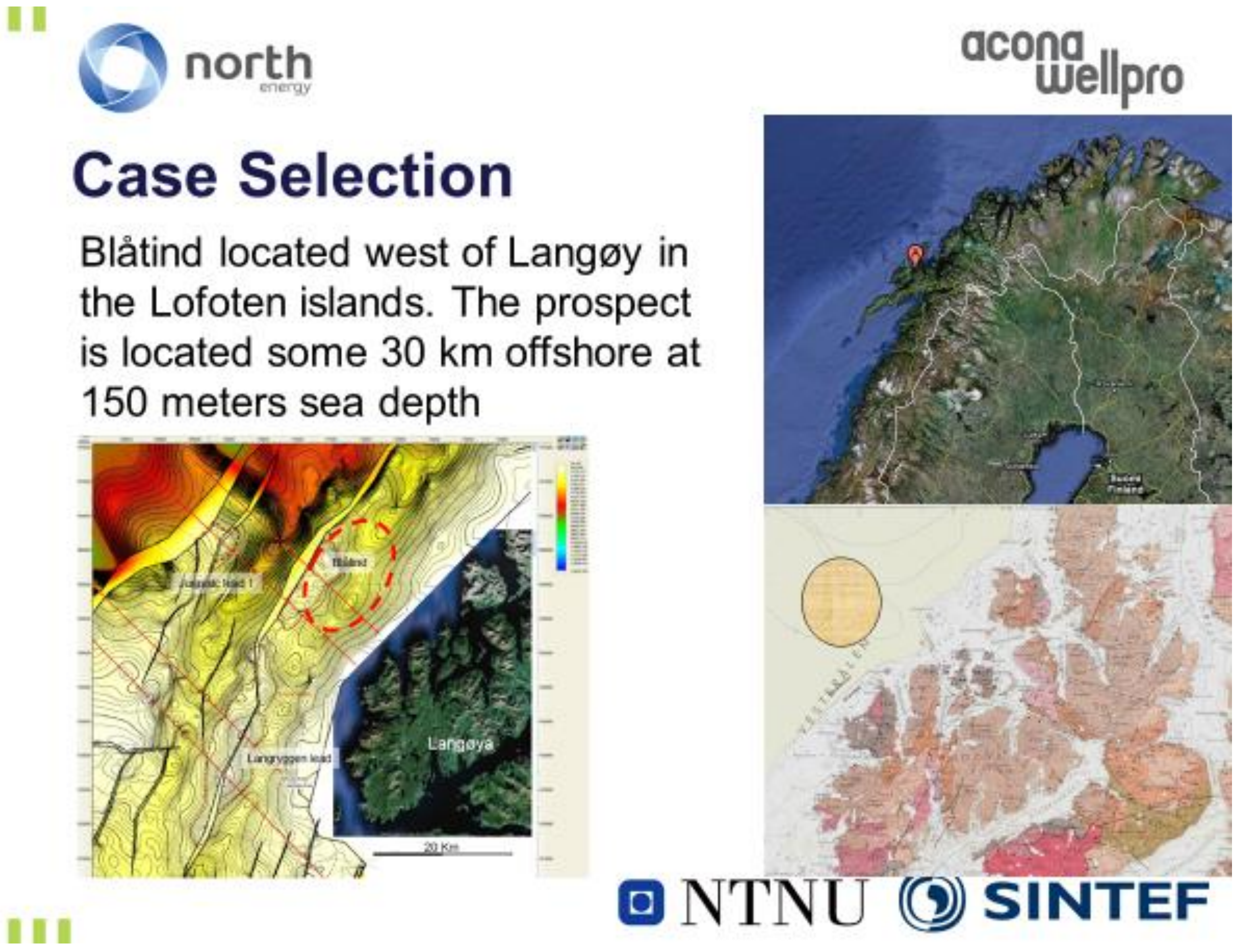
TBM APPLICATION III – Rogfast sub sea tunnel

Conclusions from the study

- TBM is a feasible excavation method for the Rogfast tunnel
- A two-tube solution is preferred to a doube-deck solution in case of TBM
- Cost per meter is appr. 20-35 % higher for a TBM than D&B in our case
- Construction time is appr. 1,6 year shorter for TBM that D&B
- TBM produces less constuction risk than D&B
- Dual Mode TBM with double shield and EPB-capacity provides increased precaution/redundancy in adverse ground conditions
- There is a need to develop further the TBM techology to provide robust solutions for such as 390m water head
- The geological conditions are complex and final choice of machine type may be evaluated following suplementary investigations

TBM APPLICATION III – Tunnel to oilfields

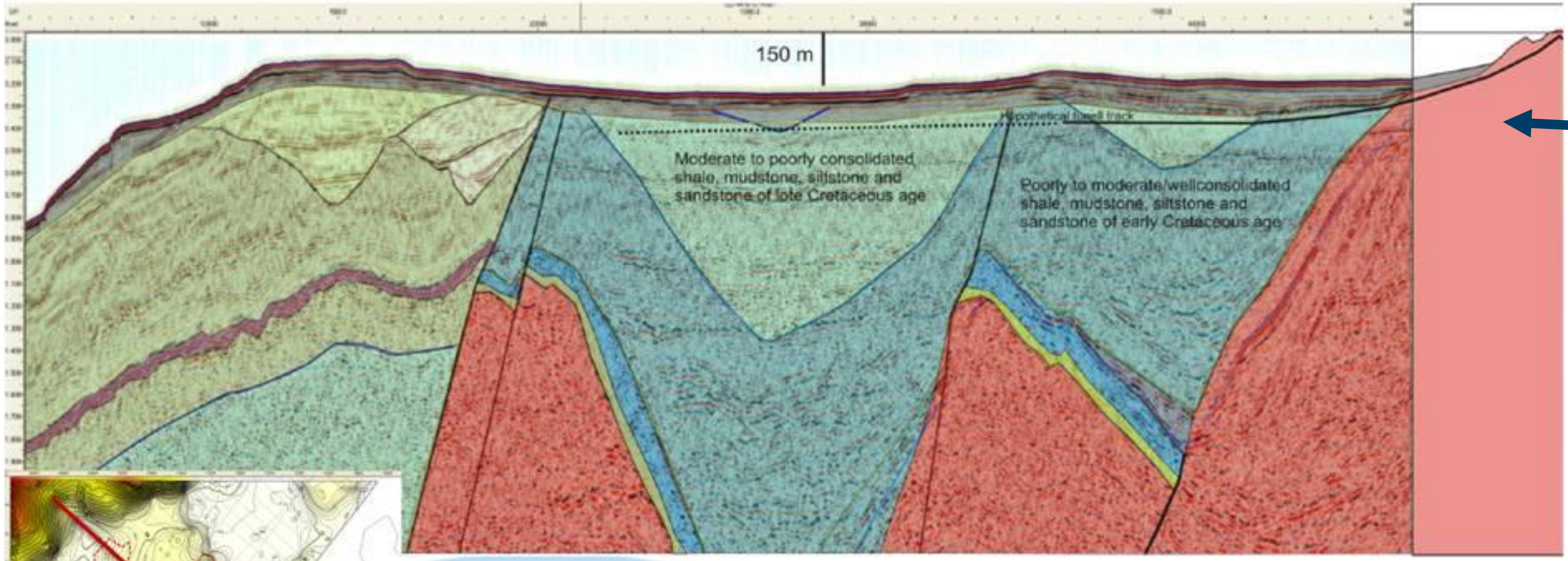


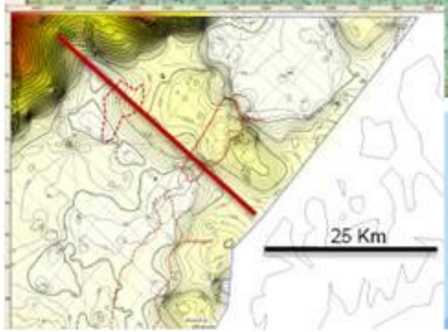


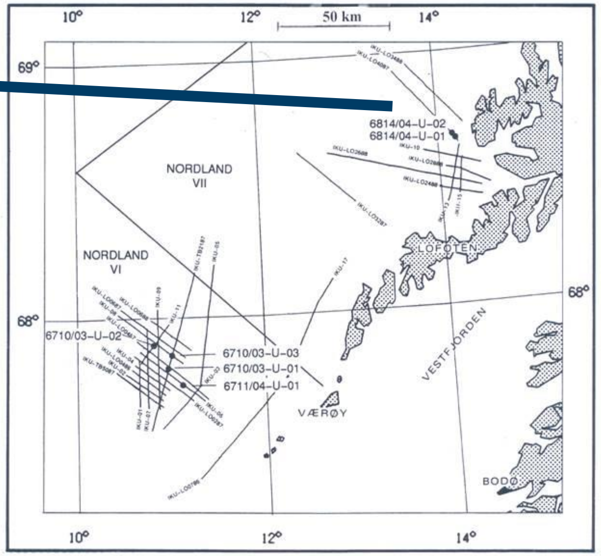
TBM APPLICATION III – Tunnel to oilfields

Geological Profile

2/3-3/4 of the tunnel is to be excavated in “moderate to poorly consolidated shale, mudstone, siltstone and sandstone” mainly of late Cretaceous age







Most of the Lower and Upper Cretaceous successions consist mainly of moderately consolidated to poorly consolidated shale with some intercalations of sandstone intervals. Some thin carbonate (limestone and siderite) may be present but will only constitute small volumes.

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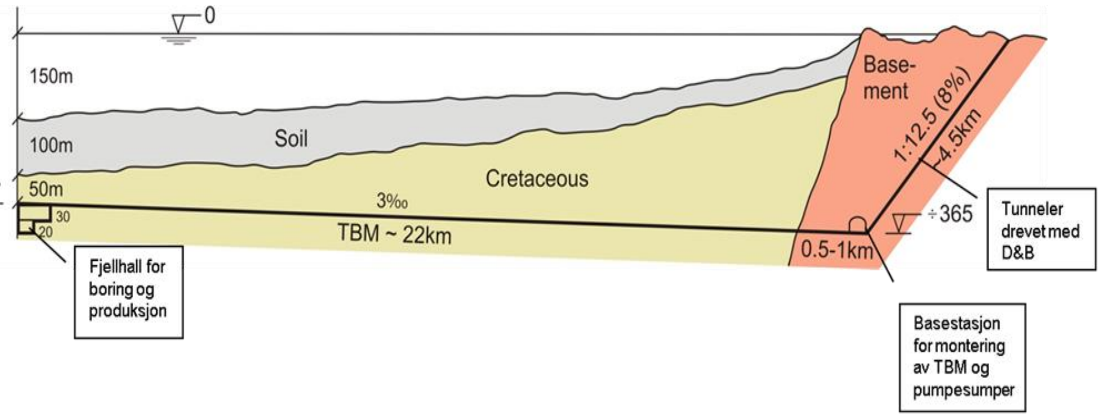
TBM APPLICATION III – Tunnel to oilfields

Available Core Samples

Shistose and heavily fractured claystone on the left, less fractured, marly siltsone on the right. UCS of 60MPa and less. Partly of very poor quality

TBM APPLICATION III – Tunnel to oilfields

TBM Challenges



1. Very weak and unstable rock mass, incl. running ground, swelling rocks etc.
2. Stress related problems (squeezing etc.)
3. Large water ingress/high pressure - pregrouting
4. Gas pockets/shallow gas
5. Mixed face conditions
6. Simultaneous drilling at 3 headings to reach high performance

Transport of muck by conveyor belts,
Transport of personnel and goods by train and wagons

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TBM APPLICATION III – Tunnel to oilfields

Cost & time Evaluations

	Subsea-to-shore 30 MSm^3	FPSO 30 MSm^3	Tunnel 30 MSm^3
CAPEX [MNOK]	22 533	22 118	22 634
OPEX [MNOK]	821	1013	703
NPV (US$ 70) [MNOK]	11486	11438	8940
Break-even [US$]	41,4	41,3	43,6

EUREKA

LICHTENBERG ANALYSIS UNDERGROUND EXCAVATION,
Max/min-time estimate

ELEMENT	UNIT	Lower estimate, Ll	Expected value, Vl	Upper estimate, Lu	Mean Value	Mean time week
Geoinvestigation	m	20000	27000	50000	30200	0
Inclined D&B T9.5	m	4500	4500	6000	4800	29
Inclined D&B support	m	4500	4500	6000	4800	15
Cross overs D&B	m	35	85	250	108	1
Base station, incl. support	No.	1	1	1	1	10
D&B basement T9.5	m	0	200	1200	360	2
D&B basement support	m	0	200	1200	360	1
TBM cretaceous ø6.6	m	20000	22000	27000	22600	83
TBM cretaceous support	m	20000	22000	27000	22600	26
TBM main boundary	No.	1	1	1	1	11
Cross overs TBM	m	60	120	480	180	14
Change TMB to RH	No.	1	1	1	1	3
Cavern excavation	m3	65000	75000	90000	76000	8
Cavern support	No.	1	1	1	1	9
Mobilization/operation						0
Unforeseen						0
Total time consumption						211
Standard deviation						16

D&B = 115m/uke

TBM = 210m/week

Total construction time = 211 weeks (168hrs/week)

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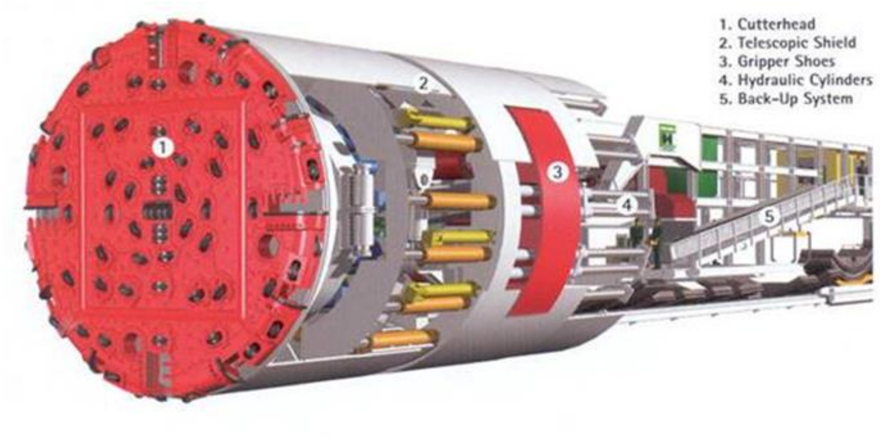
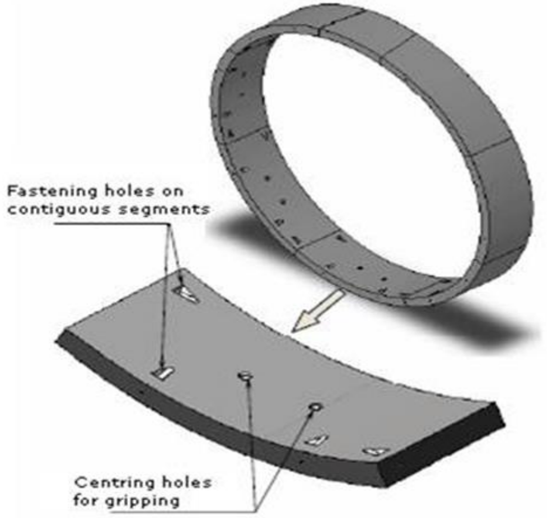
TBM APPLICATION III – Tunnel to oilfields

TBM – chosen type of machine



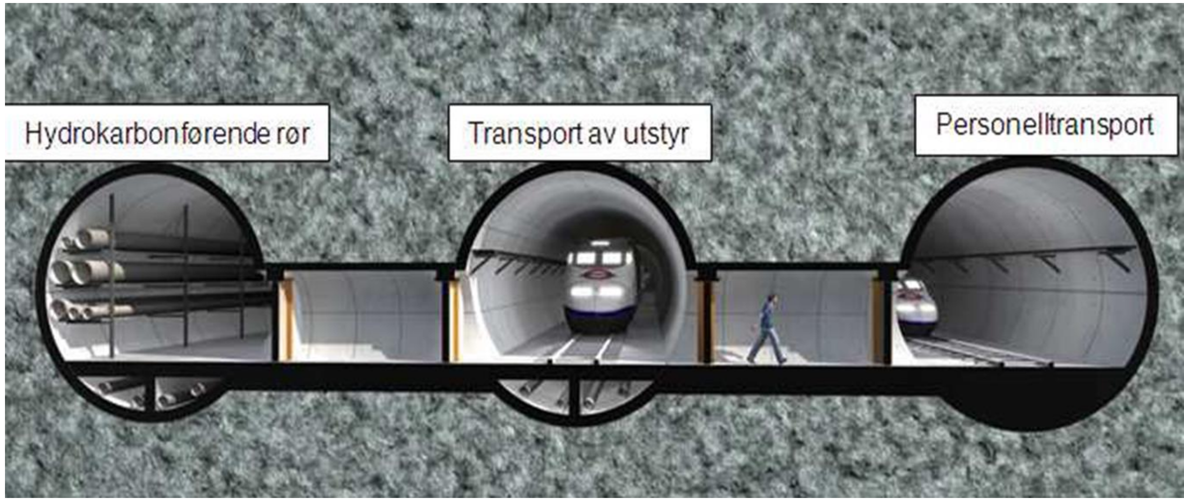


- Expected Ø=6,6m
- Double shield
- A standard TBM may not be applicable
- A custom design model to be able to tackle the various difficulties may be needed

TBM APPLICATION III – Tunnel to oilfields

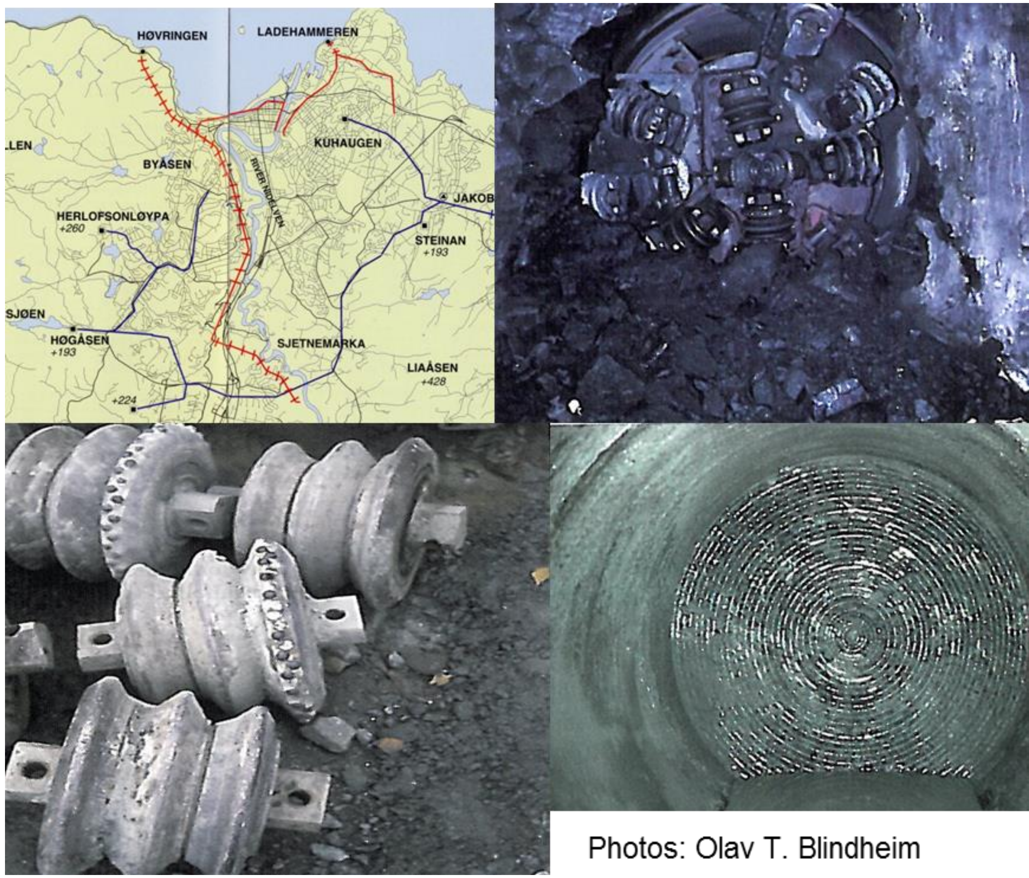
Main Conclusions on oilfield tunnels

- Tunnel solution is a realistic alternative to conventional solutions in coastal areas (around 50 km from shore).
- Risk level for personnel is acceptable and probably lower than conventional solutions.
- Key Cost/Schedule uncertainties:
  - ✓Rock quality
  - ✓Length of tunnel
  - ✓TBM performance



TBM APPLICATION III

- Norway has a long TBM-tradition
- It all started here in Trondheim
- A sewage water tunnel underneath Byåsen
- Dates back to the early 70'ies
- The client was the Municipality of Trondheim
- Enjoy the stay here in Trondheim



Photos: Olav T. Blindheim

Thank you for your kind attention