Sub-sea tunnels and lake taps in Norway - a short overview

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Sub-sea tunnels are those tunnels, which pass beneath the sea or a lake bottom; where the geology is hidden by water, see Figure 1. They are more affected by geological uncertainties and risks than most other tunnel projects because of the limited geological information and the close proximity of large amounts of water.

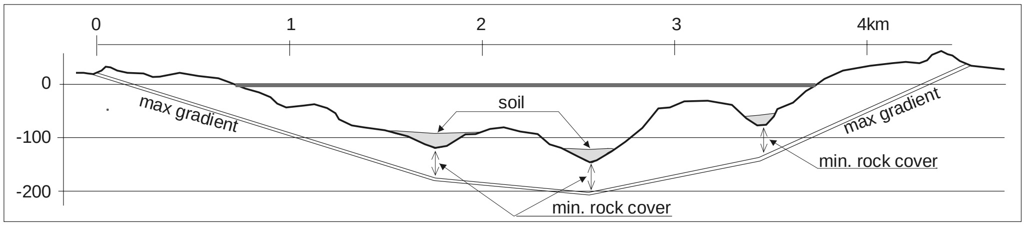

FIGURE 1 MAIN FEATURES DETERMINING THE ALIGNMENT OF A SUB-SEA TUNNEL

Looking back on earlier tunnel projects in Norway, there are many tunnels, especially in conjunction with hydropower projects, which pass under rivers and lakes and which may be classified as sub-sea tunnels. Specially in this connection are the intakes to reservoirs consisting of submerged bottom piercings or "lake taps", a specialty in Norwegian tunnel construction, see Figure 2. More than 500 of these have been constructed over the years, and more than 70 have been made since 1980. A list of some lake taps/tunnel piercings is shown in Table 3.

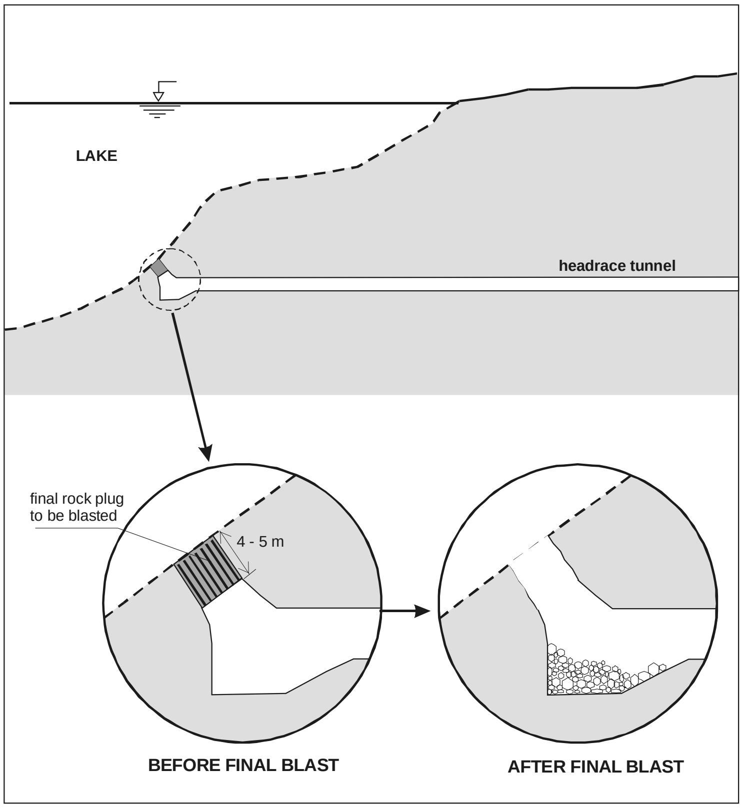

FIGURE 2 PRINCIPLES IN THE NORWEGIAN LAKE TAP METHOD

The total length of all sub-sea tunnels constructed in Norway during the last 75 years is not known, but is crudely estimated at 100km. The first sub-sea road tunnel was constructed in 1982, see Table 1. Since then, more than 85km of such tunnels have been excavated. Their locations are shown in Figure 4.

From Table 1 it can be seen that the deepest sub-sea tunnel in Norway - the Hitra tunnel - was constructed in 1994. It has 40m rock cover at its deepest point 267m below sea level.

All sub-sea tunnels in Norway have been excavated by the drill and blast method. Lake taps have also been performed by blasting the final rock plug, except for some of the piercings made for the oil-/gas pipe landfalls for which the final holes through have been made by the reaming method (not shown in this article).

Alignment of a sub-sea tunnel is determined by geological and topographical conditions as well as the tunnel's maximum gradient requirement (see Figure 1). The minimum distance for safety between the tunnel roof and the rock surface under the sea, otherwise known as the rock cover, is a crucial dimension for locating a sub-sea tunnel, Figure 3. Figure 4 shows the minimum rock cover used in Norwegian sub-sea tunnels.

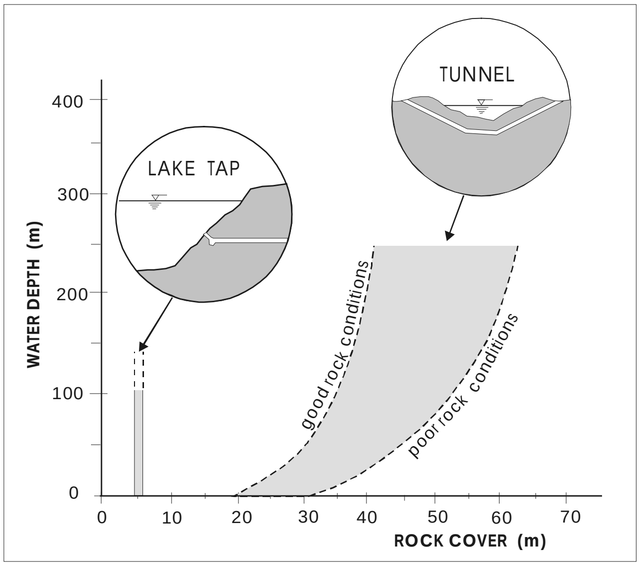

FIGURE 3 NORWEGIAN PRACTICE REGARDING MINIMUM ROCK COVER

Although there has been a continuous development in sub-sea tunnel construction since the start of lake taps in 1905, more systematic improvements have taken place during the last 20 years due to the increase in sub-sea tunnelling activity. Here, the improvements in geophysical site investigation techniques have been important. Results from acoustic profiling and refraction seismic measurements are vital for tunnel alignment planning. A map of the sea bottom is obtained from the acoustic profiling which gives the distribution and thickness of loose deposits (soil). The refraction seismic measurements give additional information on the rock mass quality and a more accurate location of the rock surface.

Developments in equipment have also resulted in a faster execution of field investigations, better data processing, and consequently, a reduction of investigation cost, which now, for sub-sea tunnels amounts to 2.5 - 7% of the total construction cost.

In addition to the use of advanced field investigation methods, the special challenges of sub-sea tunnelling require thorough planning and execution of the excavation works. The following safety measures, important for safe tunnel construction, are standard today in sub-sea tunnelling:

- Systematic 20 - 30m long exploratory drill holes ahead of the tunnel working face.
- Additions, longer exploratory core drill holes where possible poor quality rock masses can be expected.
- High pressure pre-grouting if water bearing zones and/or poor rock mass qualities have been detected in the exploratory holes.
- A high pumping capacity for de-watering the tunnel in case of unforeseen water ingress.
- High capacity application of fibrecrete quickly after blasting in order to support poor stability rock masses of short stand-up time.

These measures reduce the possibility of tunnelling problems caused by unforeseen ground conditions. In addition, a continuous exchange of experience and a close cooperation between engineering geologists, planners and contractors has been the key to the successful constructions.

A good number of studies have been made for possible sub-sea tunnels in the last 20 years, amongst which are 60km long tunnels from the Norwegian mainland to some of the nearer offshore oil fields and a 45km long railway tunnel beneath a deep fjord. Several other sub-sea projects are at the planning stage. A list of planned sub-sea road tunnels is shown in Table 2.

Table 1 Sub-sea tunnels constructed in Norway after 1975

Year completed	**Tunnel name**	**Type**	**Length** (km)	**Deepest point** (m)	**Cross section** (m^2)	**Rocks encountered**
1976	Frierfjord	O	3.6	-253	16	gneiss, claystone
1976	Vollsfjord	W	1.5	-80	8 / 16	gneiss
1980	Slemmestad	W	1.0	-93	10	claystone, limestone
1982	Vardö	R	2.6	-88	46	slate and sandstone
1983	Kårstö I	W	0.4	-58	20	phyllite
1983	Kårstö II	W	0.3	-30	20	phyllite
1984	Karmsund	O	4.7	-180	26	gneiss, phyllite
1984	Fördesfjord	O	3.4	-160	26	gneiss
1984	Förlandsfjord	O	3.9	-170	26	gneiss, phyllite
1987	Ellingsöy	R	3.5	-140	68	gneiss
1987	Valderöy	R	4.2	-137	68	gneiss
1987	Hjartöy	O	2.3	-110	26	gneiss
1987	Alvheimsund	O	1.3	-60	20	gneiss
1988	Kvalsund	R	1.5	-56	43	gneiss
1989	Godöy	R	3.8	-153	48	gneiss
1989	Flekkeröy	R	2.3	-101	46	gneiss
1989	Hvaler	R	3.8	-120	45	gneiss
1990	Nappstraum	R	1.8	-60	55	gneiss
1990	Maursundet	R	2.3	-93	43	gneiss
1990	Fannefjord	R	2.7	-100	43	gneiss
1991	IVAR, Jaeren	W	1.9	-80	20	phyllite
1991	Kalstö	O	1.2	-100	38	greenstone
1992	Byfjord	R	5.8	-223	70	phyllite
1992	Mastrafjord	R	4.4	-132	70	gneiss
1992	Freifjord	R	5.2	-130	70/54	gneiss
1994	Tromsöysund (two tubes)	R	3.4	-101	2 x 57	dioritic gneiss
1994	Hitra	R	5.3	-267	70	gneiss
1995	Troll	O	3.8	-260	66	gneiss
1996	Bjoröy	R	2.0	- 88	43	gneiss
1997	Slöverfjord	R	3.3	- 120	55	gneiss, mangerite
1997	Lysaker	W	0.6	-73	19	claystone
1999	Nordkapp (Magerøysund)	R	6.9	- 150	43	mica schist, quartzite
1999	Kårstö III	W	3.0	-60	22	phyllite
1999	Kårstö IV	W	0.6	-10	22	phyllite
2000	Fröya	R	5.3	- 164	43	gneiss
2000	Oslofjord	R	7.3	- 120	70	gneiss, amphibolite
2000	Ibestad	R	3.4	- 112	43	gneiss
2000	Bömlafjord	R	7.9	- 263	70	greenstone, gneiss
2002	Skatestraum	R	1.9	- 80	43	gneiss

R = SUB-SEA ROAD TUNNEL
W = SUB-SEA WATER TUNNEL
O = SUB-SEA TUNNEL FOR OIL / GAS PIPELINE

Table 2 Some planned Norwegian sub-sea road tunnels

Tunnel name	**County**	**Length** (km)	**Rocks**
Björvika - Bispevika	Oslo	0.7	claystone
Hadselfjorden	Nordland	9.0	gneiss
Eiksund	Möre og Romsdal	7.8	gneiss
Averöy	Möre og Romsdal	5.8	gneiss
Ryfast	Rogaland	13.0	gneiss
Finnfast	Rogaland	5.0 - 6.0	gneiss
Hidrasundet	Vest-Agder	2.6	gneiss
Boknafjorden	Rogaland	24.5	gneiss

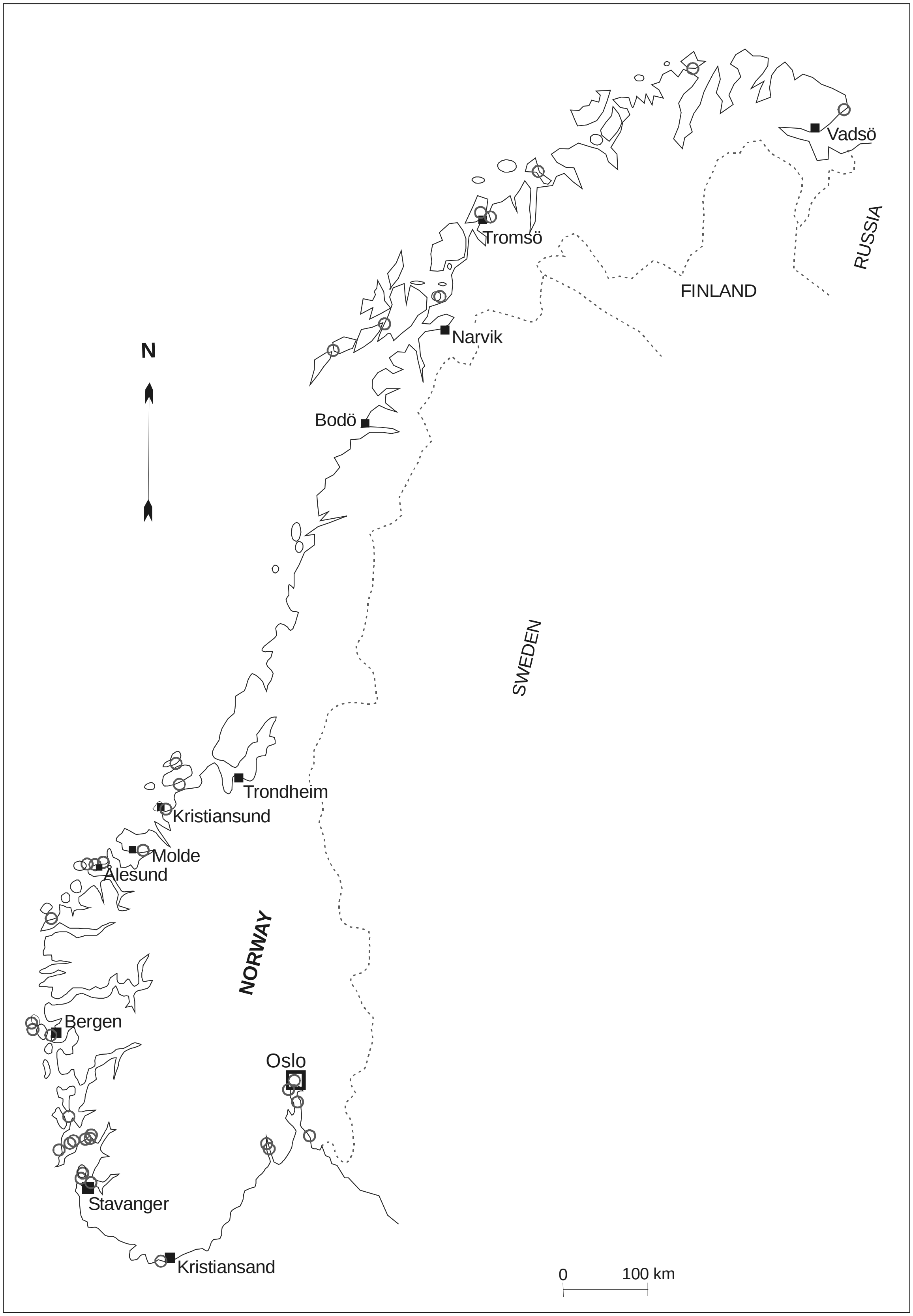

FIGURE 3   NORWEGIAN SUB-SEA TUNNELS

Table 3 Some lake taps/tunnel piercings performed in Norway after 1980

Year	**Project**	**Type**	**Number of piercings**	**Water depth** (m)	**Rocks**
1980	Aurland	H	4	15 - 22	gneiss
1980	Kjela	H	1	48	gneiss
1980	Holen	H	1	45	gneiss
1980	Vangen	H	2	21 - 22	gneiss
1980	Oksla	H	1	85	gneiss, granite
1980	Eidfjord	H	5	9 - 52	gneiss
1980	Slemmestad	W	1	40	claystone
1981 - 83	Reppa	H	2	10 - 15	phyllite
1981 - 84	Aurland II	H	10	10 - 30	gneiss, phyllite
1982	Sörfjord	H	1	70	mica schist
1983	Lomen	H	2	20	phyllite
1983	Mosvik	H	1	40	amphibolite, mica gneiss
1984	Tjodan	H	4	15 - 25	gneiss
1984	Bergsbotn	H	1	12	granitic gneiss
1986	Ulla Förre	H	8	36 - 101	gneiss, phyllite
1986	Skarje	H	2	6 - 20	gneiss
1986	Eikelandsosen	H	1	60	granitic gneiss, phyllite
1986	Kobbelv	H	7	5 - 120	gneiss, mica schist
1986 - 89	Jostedal	H	6	16 - 73	gneiss
1987	Hjartöy	O	1	80	gneiss
1989	Mel	H	4	30 - 90	gneiss
1986	Nyset-Steggje	H	2	10 - 17	gneiss
1991	IVAR, Jaeren	W	2	40 - 80	phyllite
1991	Kalstö	O	1	60	gneiss
1995	Troll	O	2	250	gneiss
1999	Kaarstö	O	2	20 / 60	phyllite

H = LAKE TAP/TUNNEL PIERCING FOR HYDROPOWER DEVELOPMENT
W = TUNNEL PIERCING FOR SEWERAGE OUTLET
O = TUNNEL PIERCING FOR SHORE APPROACH OF GAS/OIL PIPELINE