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The Challenge of Subsea Tunnelling

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Abstract—*This paper introduces the concept of subsea tunnels, and reviews Norway's experience with such tunnels. Some early tunnels in Norway involved intakes to reservoirs consisting of submerged bottom piercings, or "lake taps." Since the introduction of this method in 1905, more than 500 lake taps have been performed in Norway. The author also discusses the developments that have contributed to the increasing use of subsea tunnels, and mentions several future tunnels planned in Norway.*

Résumé—*L'article présente le concept des tunnels sous-marins et passe en revue l'expérience de la Norvège en ce qui concerne ces tunnels. Les tout premiers tunnels sous-marins norvégiens comportaient des prises d'eau dans des réservoirs conçus comme des percées submergées en fond d'ouvrage, ou "lacs robinets". Depuis l'introduction de cette méthode en 1905, plus de 500 "lacs robinets" ont été exécutés en Norvège. L'auteur présente également les développements qui ont conduit `a avoir de plus en plus recours aux tunnels sous-marins, et mentinonne plusieurs tunnels dont la construction est prévue en Norvège.*

Introduction

Subsea tunnels pass beneath the sea or a lake bottom, where the geology is hidden by water. 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.

History

The first subsea road tunnel in Norway was constructed in 1982. Since then, more than 45 km of subsea tunnels have been excavated. Figure 1 shows the main subsea tunnels constructed in Norway. Table 1 lists relevant data about Norwegian tunnels built since 1980.

In earlier Norway tunnelling projects, many tunnels, especially those constructed in conjunction with hydropower projects, passed under rivers and lakes. Intakes to reservoirs consisting of submerged bottom piercings or "lake taps," a specialty in Norwegian tunnel construction, number more than 500, 70 of which have been made since 1980. Table 2 lists lake taps/tunnel piercings performed in Norway since 1980.

The total length of all subsea tunnels constructed in Norway during the last 75 years is not known. In Figure 1 it has been estimated at approximately 80 km. The deepest subsea tunnel in Norway was constructed in 1974. It has a 50 m rock cover at its deepest point: 253 m below sea level.

Experience

All subsea tunnels in Norway have been excavated by the drill-and-blast method. Piercings/lake taps have also been performed by blasting the final rock plug, except for the piercing performed at Kalstö (see Table 2), where the final hole was made by the reaming method.

Alignment of a subsea tunnel is determined by geological and topographical conditions, as well as the tunnel's maximum gradient requirement (see Fig. 2). 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 subsea tunnel. Figure 3 shows the minimum rock cover used in Norwegian subsea tunnels.

Although there has been continuous development in subsea tunnel construction since the start of lake taps in 1905, more systematic improvements have taken place during the last 10–15 years, in conjunction with the increase in subsea tunnelling activity. Many of these improvements involve geophysical site investigation techniques, represented by refraction seismic measurements and acoustic profiling. Results from these field 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. 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 and better data processing; and, consequently, a reduction of cost—which, for subsea tunnels, now amounts to 2.5–7% of the total construction cost (see Fig. 4).

New and promising geophysical techniques under development are the radar and cross-hole methods. Several papers in *Norwegian Subsea Tunnelling* (1992) describe the geophysical investigations carried out for subsea projects.

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

- Systematic 20–30-m-long exploratory drill holes ahead of the tunnel working face.

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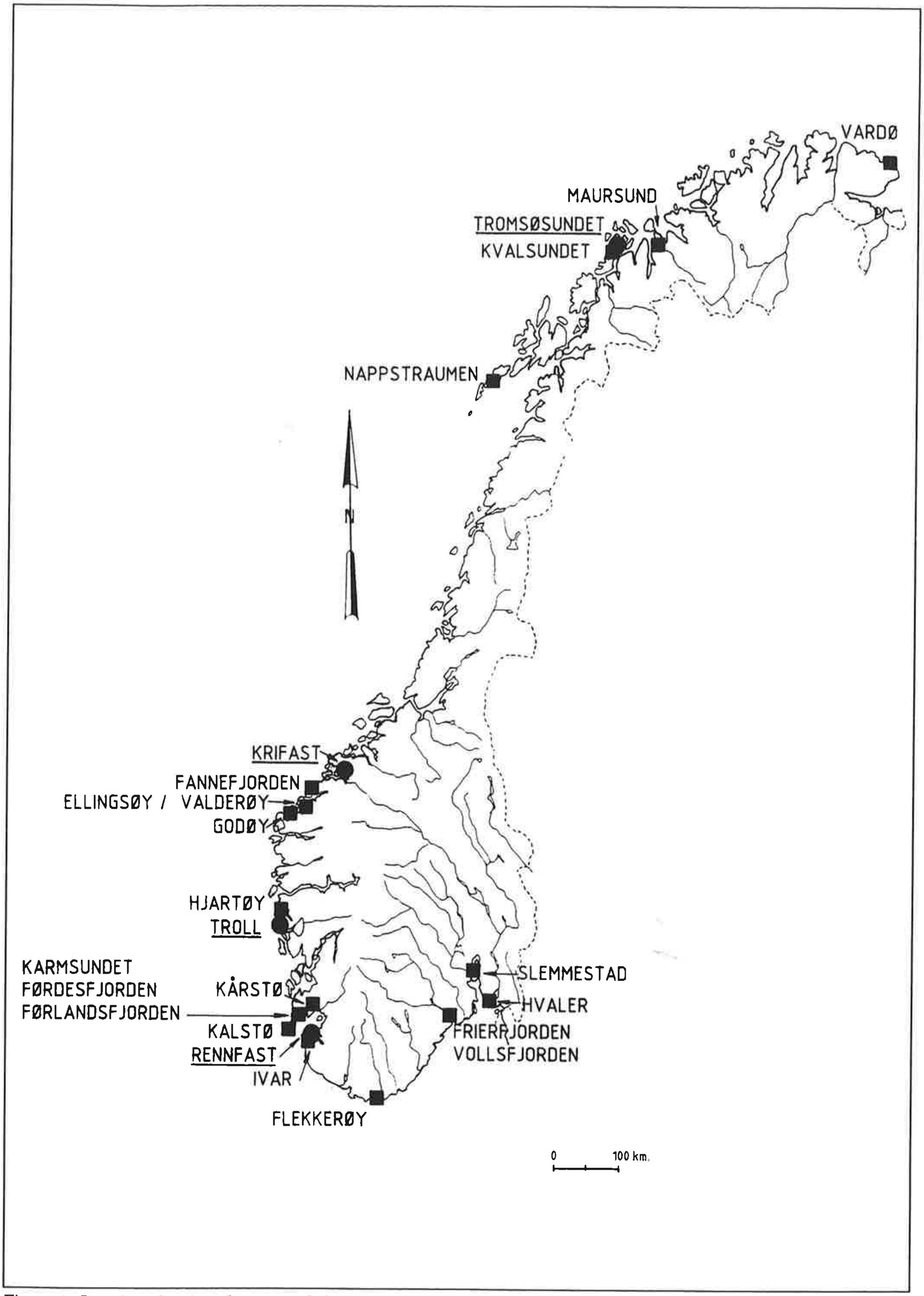

Figure 1. Location of main subsea tunnels in Norway.

- Additional, longer exploratory core drill holes where possible poor quality rock masses can be expected.
- High-pressure pregrouting, if water-bearing zones and/or poor rock mass qualities have been detected in the exploratory holes.
- A high pumping capacity for dewatering the tunnel in case of unforeseen water ingress.
- High-capacity application of fibrecrete soon after blasting in order to support poor stability rock masses with short stand-up time.

All of these measures reduce the possibility of tunnelling problems that can be caused by unforeseen ground conditions.

A continuous exchange of experience and close cooperation among engineering geologists, planners, and contractors has been the key to most of the

Table 1. Subsea tunnels constructed in Norway after 1980.

Project	Tunnel Type*	Year Completed	Cross-Section (m^2)	Main Rock Types	Total Length (km)§	Lowest Level (m)
Slemmestad	W	1980	10	Claystone, sandstone	1.0	-93
Vardø	R	1982	46	Shale, limestone	2.6	-88
Kårstø	W	1983	20	Phyllite	0.4	-58
Karmsund	O	1984	26	Gneiss, phyllite	4.7	-180
Førdesfjord	O	1984	26	Gneiss	3.4	-160
Førlandsfjord	O	1984	26	Gneiss, phyllite	3.9	-170
Ellingsøy	R	1987	68	Gneiss	3.5	-140
Valderøy	R	1987	68	Gneiss	4.2	-137
Hjartøy	O	1987	26	Gneiss	2.3	-110
Kvalsund	R	1988	43	Gneiss	1.5	-56
Godøy	R	1989	48	Gneiss	3.8	-153
Hvaler	R	1989	45	Gneiss	3.8	-120
Flekkerøy	R	1989	46	Gneiss	2.3	-101
Nappstraumen	R	1990	55	Gneiss	1.8	-60
Maursundet	R	1990	43	Gneiss	2.3	-93
Fannefjord	R	1990	43	Gneiss	2.7	-100
IVAR, Jaeren	W	1991	20	Phyllite	1.9	-80
Kalstø	O	1991	38	Greenstone	1.2	-100
Byfjord	R	1992	70	Phyllite	5.8	-223
Mastrafjord	R	1992	70	Gneiss	4.4	-132
Freifjord	R	1992	70/54	Gneiss	5.2	-130

*R = road tunnel; W = Water tunnel; O = Tunnel for oil/gas pipeline.
§Total length of subsea tunnels built after 1980 = 62.7 km

Table 2. Lake taps/tunnel piercings performed in Norway after 1980.

Project	Tunnel Type*	Year Completed	No. of Piercings	Water Depth (m)	Rock Types
Aurland	H	1980	4	15–22	Gneiss
Kjela	H	1980	1	48	Gneiss
Holen	H	1980	1	45	Gneiss
Vangen	H	1980	2	21–22	Gneiss
Oksla	H	1980	1	85	Gneiss, granite
Eidfjord	H	1980	5	9–52	Gneiss
Slemmestad	W	1980	1	40	Claystone
Reppa	H	1981–83	2	10–15	Phyllite
Aurland II	W	1981–84	10	10–30	Gneiss, phyllite
Sørfjord	H	1982	1	70	Mica schist
Lomen	H	1983	2	20	Phyllite
Mosvik	H	1983	1	40	Amphibolite, mica gneiss
Tjodan	H	1984	4	15–25	Gneiss
Borgsbotn	H	1984	1	12	Granitic gneiss
Ulla Førre	H	1984	8	36–101	Gneiss, phyllite
Skarje	H	1986	2	6–20	Gneiss
Eikelandsosen	H	1986	1	60	Granitic gneiss, phyllite
Kobbelv	H	1986	7	5–120	Gneiss, mica schist
Jostedal	H	1986–89	6	16–73	Gneiss
Hjartøy	O	1987	1	80	Gneiss
Mel	H	1989	4	30–90	Gneiss
Nyset-Steggje	H	1986	2	10–17	Gneiss
IVAR, Jaeren	W	1991	2	40–80	Phyllite
Kalstø	O	1991	1	60 m	Gneiss

*H = Lake tap/tunnel piercing for hydropower development;
W = Tunnel piercing for sewerage outlet;
O = Tunnel piercing for shore approach of gas/oil pipeline.

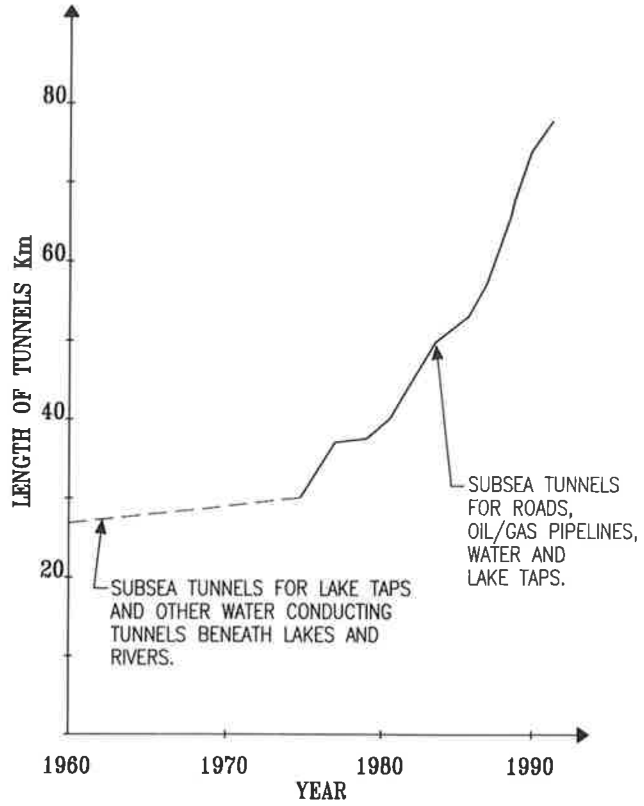

Figure 2. Development of subsea tunnel construction in Norway.

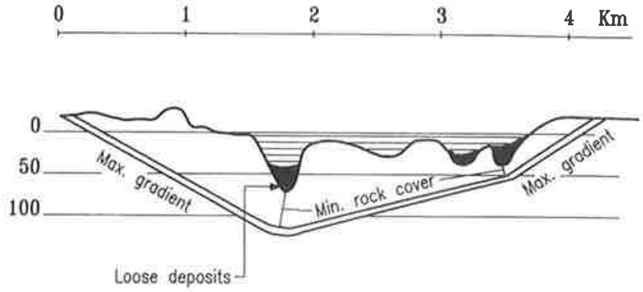

Figure 3. Main features determining the alignment of a subsea tunnel.

improvements that have been made, as well as successful constructions. Rapid tunnelling has resulted in lower excavation costs for subsea tunnels (see Figs. 5 and 6).

Present and Future Subsea Tunnel Projects

In the past ten years, a number of studies have been done for possible subsea tunnels. The possibilities include 60-km-long tunnels from the Norwegian mainland to some of the nearer offshore oil fields, and a 45-km-long railway tunnel beneath a deep fjord.

Approximately 13 km of subsea tunnels are currently under construction in Norway. Among the subsea tunnel

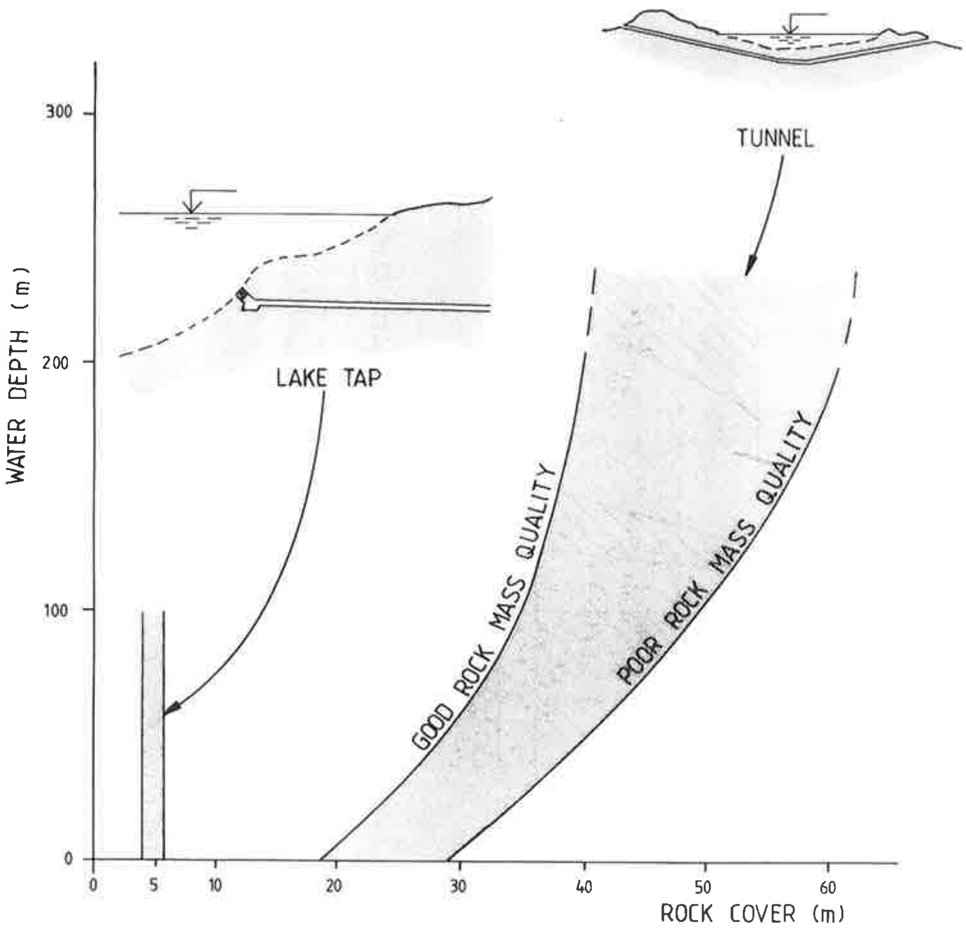

Figure 4. Norwegian practice regarding minimum rock cover. (More information on tunnel overburden is presented in articles in Norwegian Subsea Tunnelling 1992*).*

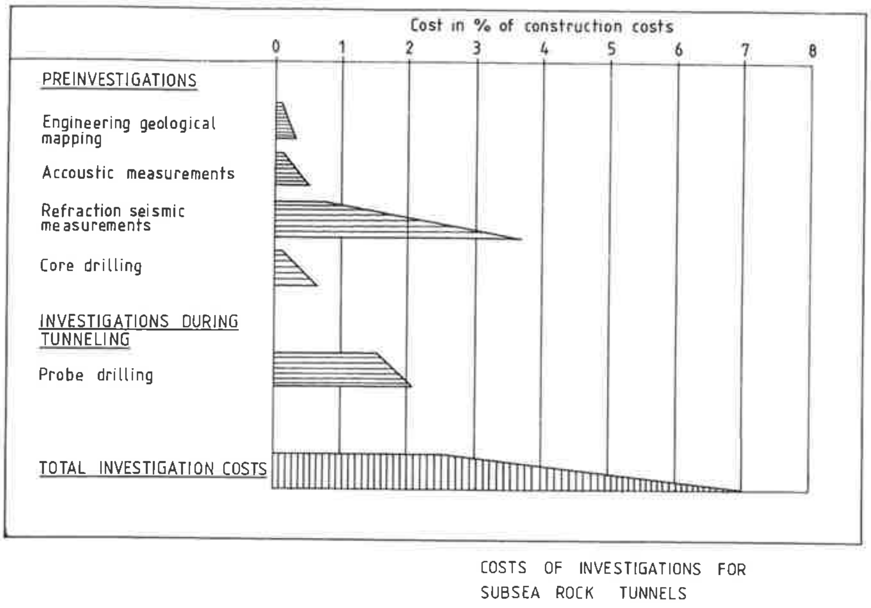

Figure 5. Approximate distribution of investigation costs for Norwegian subsea rock tunnels.

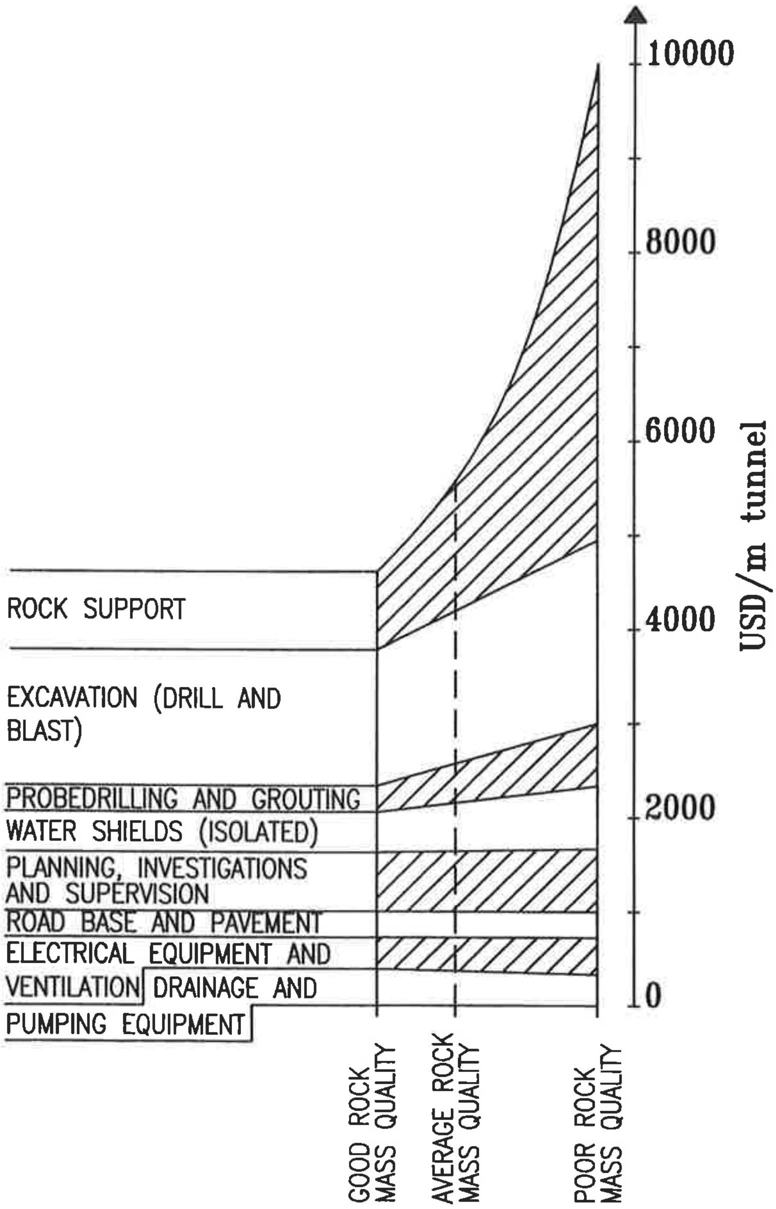

Figure 6. Approximate distribution of cost for a two-lane, 50-m² subsea road tunnel.

projects under construction as of autumn 1993, the following should be mentioned:

- Tromsöysund, a 3.4-km-long road tunnel; the deepest point will be 102 m below sea level.
- Troll, a 3.8-km-long shore approach tunnel for gas/oil pipelines. The deepest point will be 260 m below sea level, where a tunnel piercing up to the sea bottom will be performed.
- Hitra, a 5.6-km-long road tunnel; the deepest point will be 275 m below sea level.

There will be a high level of activity within the planning and construction of subsea tunnels in Norway in the coming years.

References

Norwegian Soil and Rock Engineering Association. 1992. *Norwegian Subsea Tunnelling*. Trondheim: Tapir Publishers.