CHALLENGES TO TUNNELLING ENGINEERS (1995)

Reasons for Mounting Challenges

Major tunnelling projects require 10 to 15 years to be completed. A United Nations study predicts that by the year 2010, 50% of the world's population – which by then will have grown to 7 to 9 billion people – will live in larger towns. The big cities will grow to become monstrous megalopolis areas (Fig. 1).

![Megalopolis](image)

Fig. 1: Tokyo's population is expected to climb to 30 million by the year 2010.

Although technology may never be able to compensate for what the population explosion does to the earth, tunnelling at least tries to contribute to a sustainable life for future societies by providing clean water, healthy sanitary conditions, underground trafficways, and facilities for energy, waste, and goods below the surface.
Thus, tunnelling has become a vital need, and we tunnelling engineers are confronted with ever increasing challenges and more responsibilities. We are asked to build tunnels:
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- Even in ground conditions so difficult that, hitherto, no one would have dared to excavate a tunnel,
- Under high deep sea water pressure,
- Underneath some thousands of meters of rock,
- Underneath congested town regions in bad ground, such as found in Mexico City and Bangkok,
- For more and more purposes for underground facilities, such as waste repositories and storages that meet environmental restrictions as well as objections of protesters,
- And – please – within affordable and economical financial limits, perhaps even with capital returns; and furthermore, running neither technical nor financial irresponsible risks,
- and... and...and...

Engineers are not only being asked to excavate deeper and longer tunnels faster and less costly, but the tunneller's challenges also are shifting and expanding to include environmental and social problems. Engineers may dream of providing, by going underground, a beautiful, healthy town of the future. Yet the reality looks quite different (Fig. 2).
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All this is asking almost too much. And then it happens that a tunnel drive is flooded, an excavation face fails, a TBM gets stuck, or surface buildings are threatened with collapse: And all of the mass media point an accusing finger at the engineers. All the successes achieved and all of the risks taken do not count for much against these accidents. Society is unjust. And yet engineers are a rather strange species: In spite of all these challenges and these skating-on-thin-ice risks, engineers respond with new inventions, with more ingenuity by advancing the art of engineering, and by accepting even more responsibilities.

This paper addresses some of the main challenges facing tunnellers, some of the lessons learned through recent tunnel construction, and some of the problems of projected tunnels that are challenging tunnellers today, see also [1].

![Image](image.png)

*Fig. 3: Multiple drifts for German highspeed railway tunnels.*

**Railway Tunnels in Multiple - Drift Excavations**

In mid-Germany, more than 80 tunnels, comprising a total length of more than 160 km, have been built for the high-speed railway line in large double-track cross-sections (see Fig. 3). The tunnels have been excavated in soft ground, limestone, and sandstone formations by multiple drifts and with preliminary shotcrete support. South Korea has initiated almost the same tunnelling program for its high-speed trains. The multiple-drift tunnelling method has been applied successfully in many countries. It originated from the principles of the Austrian school of tunnel engineering. Yet it has progressed beyond the origi-
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inal principles of the "New Austrian Tunnelling Method" (NATM or NÖT) and, therefore, should be free of an attached national name, thus avoiding futile quarrels over whether an excavation is NATM or not. Some of the tunnelling lessons learned, especially from some collapses at the tunnelling face [2], are:

- The unsupported excavation face is the most critical section.
- If a tunnel collapses, it is almost always the ground that fails, not the lining.
- In soft ground, the excavation procedure should not allow ground deformations to develop into shear failure lines. Hence, immediate strong support is more suitable than a flexible one, which allows some stress release. Early closure of the supporting lining is essential.
- Monitoring results inside the tunnel do not indicate what the ground has already experienced before the first reading is taken.
- Highly experienced miners, geologists, and tunnelling engineers are needed to select successful excavation sequences and support measures.
- Instead of a permanent drainage (which is easily clogged by sintering) a closed system against ground water may be preferable.
- The multiple-drift excavation method can be applied successfully even in rather soft ground conditions, although in some cases of extremely difficult ground, the application of shotcrete technology has been pushed almost to its limits.

![Interior view of the completed tunnels (artist's concept)](image)

Fig. 4: Trans Tokyo Bay road tunnel.
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Deep Sea Tunnels for Straits Crossings

The successful completion of the Seikan Tunnel, Channel Tunnel, and Storebælt Tunnel and the successful start of eight huge 14-m-diameter slurry shields of the Trans Tokyo Bay road tunnels (Fig. 4) have encouraged many authorities to begin feasibility studies and planning for other tunnels crossing straits under deep sea water [3]:
- The Øresund crossing between Denmark and Sweden (rail and road), by a combined tunnel (5 km) and bridge structure.
- The Fehmarn Belt crossing between Denmark and Germany: a railway tunnel, approx. 50 m below sea level and 19 km long, perhaps also a combination of tunnel and bridge.
- A Northumberland Straits crossing between New Brunswick and Prince Edward Island in East Canada: tunnel 13 km long, in 30 m water depth.
- The Byfjord Tunnel at Stavanger, Norway, 5.8 and 4.4 km long, 223 m and 130 m below sea level.
- The Bohai Channel project in China, between Shandong and the Liao-dong peninsula: 57 km long (the world’s longest).
- The Messina Straits crossing: either a suspension bridge with a 3300-m main span, or separate railway and road tunnels, 17 and 23 km long, 6 km of which may be submerged tubes floating 50 m below the sea surface (Fig. 5) in a water depth of 150 m.

**SUBMERGED CONCRETE TUBE**

![Diagram of submerged concrete tube](image)

Fig. 5: Submerged floating tunnel for deep straits crossing (Norwegian design).
And for enthusiastic tunnellers, never shy of visions and challenges, there are many more straits to cross the next century:

- The Gibraltar Straits Tunnel: 39 km long, 412 m below the sea level (see Fig. 6).
- Many shorter but deep tunnels crossing the fjords of Norway, such as the Oslofjord, which is 14 km long and 300 m below sea level.
- The Sunda Straits, between Java and Sumatra: 40 km wide, 200 m deep.
- The Straits of Bonifacio, between Corsica and Sardinia.
- Even the Bering Straits, between Alaska and Chukchi-Siberia: 90 km apart and with two Diomede Islands midway between them, with water depth some 30 m.
- A connection between Korea and Japan, 185 km apart with two islands Iki and Tsushima in between.
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Each tunnelling project, because of its individual features and ground conditions, is a prototype case and may demand ever new and adjusted technologies. For the feasibility study for a new project and the evaluation of the risks involved, experiences gained from past projects are of utmost importance. Thanks to the very open and frank reports by the leading engineers on the troubles they encountered – as, for example, has been documented so well for the work done in crossing the Storebælt [4] – much may be learned that will help to avoid difficult situations at the next tunnelling site.

For deep sea straits tunnels, some of the main lessons learned and challenges to be met include the following:

1. In deep ground, exploration of the geological and hydrogeological conditions is very difficult. Long-range horizontal boring ahead of the tunnel face (up to 2200 m for the Seikan Tunnel) may be indispensable.

2. Unexpected ground conditions, such as high permeability in fractured zones, may require extensive grouting.

3. For the Seikan Tunnel, the acceptance of a certain amount of permanent water ingress is intended to release the high water pressure (maximum depths 240 m, whereas the maximum depth of the Gibraltar Tunnel is 412 m, see Fig. 6). In such cases, extensive measures against salt water damage are necessary to protect grout material, concrete, reinforcement, electrical installations, and rail equipment.

4. Because of the many surprises to be expected, the engineers should provide a broad variety of technical means, which the contracts also should cover. Large projects may even need on-site innovations, not thought of and not known at the time of contracting.

5. Permanent maintenance can be much more costly than expected in the planning phase. The ingress of saline water in the Seikan Tunnel caused not only corrosion but also bacterial growth.

6. Thanks to the excellent engineering of the technical problems, the main challenges of the Channel Tunnel were related to:

- The private financing by 220 bankers and 500,000 share holders, which resulted in difficult arbitrations.

- Contract disputes, especially for the tunnel equipment work.

- Logistics that challenged management skills, especially the logistics of hauling materials, personnel, and much for such long distances.
7. Achieving a high standard of safety against accidents, fire, and terrorism carries a price. Overreaction by the public to tunnel accidents results in costly safety provisions, often demanded and expanded quite late after the start of work. Tunnellers face a dilemma: If all of the technically available safety measures are provided in order to satisfy public demands, then the costs of operation and maintenance may be so high that larger tunnel projects are no longer feasible (not to mention any capital returns). This situation may negate our efforts to achieve low-cost tunnelling.

![Diagram of Cross Passage](image)

Fig. 7: Cross-passage [3]

8. Safety considerations result in closely spaced cross-passages. Under high water pressures, these cross-passages (every 375 m at the Channel Tunnel and every 250 m at the Storebælt, as shown in Fig. 7) constitute a great technical challenge. For future tunnels, we will certainly need tunnel-boring-Machines that are specialised to drive passages under difficult conditions.

9. Some of the lessons learned form the Storebælt experiences may be considered in future projects [3, 4]:
- A proper quality control of the tunnelling machine manufacturing is absolutely essential, even when the delivery time to the site is rather short.
- Glacial till can cause very severe wear on the cutting tools.
- High pore water pressure prevents access to the cutting front of a tunnel-boring-machine (TBM).
- Hydraulic oil can cause fire, resulting in damage to machines and linings.

10. The Trans-Tokyo Bay Tunnel (Fig. 4) at present under construction is advancing our experiences into new fields:
- Can the 14 m high tunnelling face be stabilized under 50 m of water pressure at the shield center and a soft ground cover of only 10 – 16 m depth?
- How reliable is the robotic handling of the tunnel segments by computerised sensor equipment?
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- We are eager to learn that the new design for the midpoint face to face docking of two TBMs running against each other proves to be successful and economical.
- The almost simultaneous start of eight slurry shield machines from Kawasaki and two men made islands to drive two 14 m diameter tubes is a very high investment. Obviously, for larger projects the time related financial costs are so high, that eight TBMs are justified.

Challenges of Transalpine Tunnels

Four transalpine tunnels are being considered. Planning for the two tunnels in Switzerland – the Lötschberg (42 km) and the Gotthard Base Tunnel (57 km long) – has advanced much further [5, 6] than planning for the Brenner Base Tunnel (55 km) and the Mont Cenis Tunnel in France towards Torino.

![Diagram of Gotthard Base Tunnel and Channel Tunnel](image)

**Fig. 8:** Comparison of overburden for the Gotthard Base Tunnel and the Channel Tunnel [5].

The overburden of the Swiss tunnels – up to 2300 m of fissured rock (Fig. 8) and water pressure greater than 1000 m (expected permanent water ingress up to 1000 l/s) – create immense challenges on new tunnelling frontiers. The challenges begin with the geological and hydrogeological explorations, especially of deep fissure zones such as those of the Piora Syncline. Geologists may dream of a highly sophisticated computerized robot microtunnel that could be sent travelling on its own through all the mountains, providing all of the needed data on rock quality, water and temperature. But even if all these data are known, what will be the actual reaction of the deep rock to the excavation?
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What kind of tunnelling machine or drill-and-blast excavation can cope with these challenges, which go beyond those of the Vereina tunnel?

New challenges are also posed by the need to write suitable contracts, which should cover unexpected surprises, too. Finally, the financial challenges are not smaller than the technical ones. Will the projected total of 27 billion Swiss Francs, to be spent up to the year 2009, be sufficient for both base tunnels? Is there an almost natural law that the final price of big tunnelling projects will exceed the original price estimate, often by a considerable amount? And what will be the actual operation costs of the finished project when financial interest rates and maintenance are included?

**Fig. 9: Alternatives for the Weser Tunnel north of Bremen.**

**Shallow Tunnels**

For many shallow tunnels under waterways, we have the option between immersed tubes and bored tunnels. As an example, Fig. 9 shows the investigated alternatives for the planned Weser Tunnel north of Bremen [7]. The shield driven tunnel is longer by 180 m (8 %) and 10 m deeper. Nevertheless, the bored tunnel is selected for tendering, because of environment arguments for less surface areas being disturbed and because of a law of Lower Saxony that the construction which has the least impact on nature has to be chosen, regardless of compensation advantages of other solutions. The circular cross section of the bored tunnel is not optimal: The lost
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areas above and underneath the required traffic cross section result in greater depth and greater water pressure, increasing the risks of hazards. So, perhaps, it may be wise to decide in favour of an immersed tunnel for the underground section of the Øresund crossing rather than for a bored tunnel. In future, we may meet environmental concerns halfway, perhaps by pushing immersed tunnel elements one behind the other from one shoreline as in the method for building bridges ("Taktschiebe-Verfahren").

Risks Assessments

As demands for underground structures to be constructed — regardless of the ground conditions — have increased, safety and risks considerations have taken on ever greater importance. A number of more systematic approaches to the planning and engineering of such structures have been proposed [8]. First, we need to determine which potential risks a specific project runs at all, and second, these risks have to be assessed. Feasibility studies and, even more importantly, tenders and contracts, must deal with at least the following categories of risks and potential hazards:

- Financial risks, such as cost overruns or lower than projected rates of capital returns,
- Contractual risks, such as additional work not covered, time delays, disputes, claims,
- Ground conditions, such as unexpected geological or geomechanical features, overrating of ground reaction to excavation, or more water ingress than expected,
- Constructural risks, such as tunnelling machine failures, cutting tools wearing out too fast, face collapses, or sealing leaks,
- Environmental risks, such as impairing ground water, use and recultivation of land, and air or noise pollution,
- Functional risks, such as long-term performance, too steep an alignment, or traffic impediments created by a need for heavy maintenance.

For tunnelling, the list of what may go wrong, is long and very diverse. The potential damages in each case or scenario are very different. Therefore, risk analyses are so important and must take into account short-term and long-term risks, and the probability and extent of potential damages. Some risks,
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such as environmental damages or loss of human life, cannot be evaluated in
terms of costs. Hence, different assessment criteria are needed.

From some of the tunnel experiences and lessons learned, it may be stated
that:
- The "unexpected" problems are the ones most likely to occur. What mostly
  happens is that we are simply unaware of critical situations.
- There is a tendency that those troubles occur that we are least prepared for
  (another Murphy's law?).
- Therefore, brainstorming sessions should address also the most "stupid"
  potential causes of accidents, including human errors: The wrong welding
  spot on high-strength steel, the forgotten lamp cable, the over-confidence
  resulting from a period of better-than-expected performance.
- At least in initial risk assessments, worst-case scenarios even of small
  probability should be considered seriously.

There is still very much to be done in the field of consistent risks assessment.
This is a challenge for all of us, especially when risk avoidance impedes
innovations.

Tunnels for Mega – Projects
or better for Sewers and Metros in Megalopoli?

As so often stated, tunnelling engineers promise to contribute to a "more healthy
and sustainable life for all the world's people". Therefore, our profession should
not be content with technology, financing, and operation of tunnel projects. We
should go beyond this, toward influencing the decisions made in selecting
projects of national and international importance, especially when public
financing is involved. If the International Tunnelling Association and tunnellers
all around the world are promoting underground use for the benefit of mankind,
then we also must raise our voices when priorities have to be set.

The Gibraltar Straits tunnel (Fig. 6) may serve as an example for clarifying
arguments. It is foreseeable that this project will require substantial financial
subsidies (e.g., from the World Bank) for construction as well as for operation.
Excavating a tunnel with all the cross-passages more than 400 m below sea
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level (see Fig. 6), is certainly an exceptional challenge to engineering ingenuity, and undoubtedly will contribute to the progress of the art of tunnelling. However, in the light of our broader responsibility, some questions and reflections arise:

- The world has become a smaller place. The resources for megaprojects are limited. If public funding goes into a project, and in view of mankind's struggle to survive, will a railway line underneath the Gibraltar Straits win priority over, for example, sewers in Lagos or a metro in Shanghai?
- If the rapidly growing megalopolis areas are being suffocated by traffic and by pollution, if humans in so many regions of the world are in need of clean water and healthy sanitary conditions, should not engineers be at the front line to convince the (sometimes prestige-hungry) politicians of what should come first?
- A somewhat simplified estimate yields the following results. Assumed that the Gibraltar tunnel may require the same amount of money as the Channel Tunnel, say 20 billion US $, then this would be equivalent to:
  
  3000 km (!) of sewer tunnels, or
  600 km (!) of underground metro lines.
- For how many years could all the ferries run across the sunny Straits of Gibraltar without asking for crossing charges, if they could get the amount of money subsidized for the operation of the tunnel and for serving the financial loans?
- Of course, humankind – and, hence, also engineers – do need "a man on the moon," some very challenging projects, the Seven Wonders of the ancient world, the largest cathedral, the rocket into outer space. Yet there are limits to the victory of the intellect over reason ("Sieg des Verstandes über die Vernunft", Max Born).
- Succeeding to divert public financial resources from "white elephant" projects to tunnels for water, sewage and for metro lines in needy megalopolises, and to overcome all of the obstacles in actually building them: this certainly is also a great challenge to engineers.

Engineers are working on what the philosopher Karl Popper calls the "third phase" of our world. The first phase was the creation of the non-self-reproducing material world of the universe and the atom. The second phase was the evolution of the living biosphere, including brains capable of thinking. The third phase is the development of what human brains have put into the world: culture and civilisation, as religions, sciences, Mozart's music and computers, Shakespeare's plays – and tunnels (Fig. 10). Engineers place into the world what has not existed before,
what has not been imprinted in the plan of biological evolution. Engineers in the tunnelling profession are challenged by many new frontiers to develop their art. Their responsibilities have grown far beyond technique alone. What tunnellers are achieving, and will continue to achieve even more so in the future, is this: contributing to allowing humankind to live a more decent life. And that is very much in this endangered world.

Literature