PROPERTY

COMMENTARY PAPER

Boring the world's longest tunnels: innovation at work

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Classification of tunnels

The Channel Tunnel, also known as the Eurotunnel, is the world's longest underwater tunnel – connecting England and France. Comprising of two tunnels for rail and a central tunnel for services and security, it's 31 miles long under salt water. In fact, the Channel Tunnel has the longest undersea portion of any tunnel (23.5 miles) and is also the second-longest railway tunnel in the world. However, this underwater marvel is short in comparison to other tunnels around the world.

Despite most of the following being water, railway or road tunnels, all are longer than the more famous Channel Tunnel:

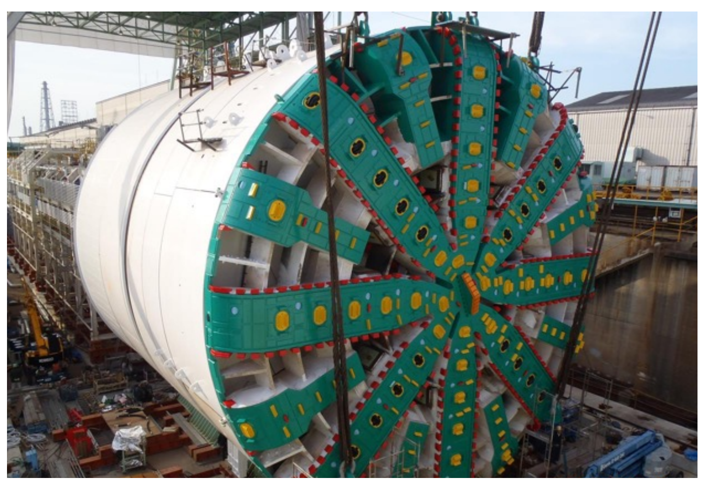
- 85 miles: The Delaware Aqueduct in New York City is the longest continuous tunnel in the world. The tunnel transports water from the Rondout reservoir to the Hillview reservoir in Yonkers.
- 74 miles: The Päijänne water tunnel located in southern Finland.
- 53 miles: Dahoufang water tunnel located in China.
- 51 miles: Orange-Fish tunnel, an irrigation tunnel located in South Africa.
- 51 miles: Bolmen water supply tunnel located in Sweden.
- 39 miles: Emisor Oriente storm water and sewage tunnel located in Mexico City.
- 37 miles: Guangzhou Metro Line 3, the longest subway tunnel, located in China.
- 35 miles (twin-bore): Gotthard Base Tunnel (in two sections) is the longest and deepest railway tunnel in the world, located in Switzerland.
- 35 miles: Beijing Subway Line 10, rapid transit tunnel located in China.

Common types of tunnels:
Mine tunnels – used during ore extraction – enabling laborers or equipment to access mineral and metal deposits deep inside the earth. These tunnels are made using similar techniques as other types of tunnels, but they cost less to build, and they are not necessarily as safe as tunnels designed for permanent occupation. **Public works tunnels** – transport water, sewage or gas lines across great distances. **Transportation tunnels** – used for cars, trains and canals.

Tunnel construction:
Cut-and-cover tunnels – involve immersing a tube in a trench and covering it to keep it in place. **Bored tunnels** – constructed on-site, without disturbing the ground above. **Immersed tube tunnels** – sunk into a body of water and laid on or buried just under its bed.

Tunnel boring machines (TBMs)

A tunnel boring machine (TBM) or "mole" as some may call it, is a machine used to excavate tunnels with a circular cross section through a variety of soil and rock. TBMs can bore through hard rock, sand and just about everything in between.



Pictured is a TBM called Bertha, the largest TBM ever built (57.5 ft.). Bertha completed boring Seattle's State Route 99 tunnel in April 2017.

TBMs are comprised of four systems:

- Boring: A system that cuts through rock with a rotating head (or cutterhead) mounted with disc cutters. As the cutterhead rotates, it presses the discs against its face, which creates a slicing motion. The high pressure the cutterhead exerts is greater than the compressive strength of the rock, and that is how it grinds it fairly easily.
- Thrust and clamping: The thrust and clamping system is designed to move the TBM forward utilizing hydraulic cylinders.
- Muck removal: The rock and soil removed by the cutterhead is mixed with water or other substances, to create a “muck” that is easier to relocate. Typically, a screw conveyer pulls the muck out to a standard conveyer belt, where the material is moved out of the tunnel and disposed of.
- Support: As they grind their way forward, TBMs have to be protected from earth falling around them. Support systems to protect the TBMs from fault zones include pipes, grout injection, rock bolts, and freezing used over or in front of the cutterhead. A roofing shield support system is used to protect workers who are behind the cutterhead.

There are two major types of TBM operational modes: open shield and closed shield. Doug Harding at Robbins Corporation notes that open mode is employed when no pressure is required to stabilize the boring face. The geology is self-standing and ground settlement will not occur. Closed mode is employed when face pressure needs to be constantly applied in order to maintain support. If face pressure is not maintained as determined by the geology, under-pressurization will cause ground settlement while over-pressure will cause surface heaving.

Open shield TBMs have single and double shield options. Single shield TBMs are enclosed in a shield that is marginally smaller than the diameter of the tunnel. The shield protects workers from fractured rock until the tunnel lining is installed. Double shield TBMs are able to erect the pre-cast concrete tunnel lining, while boring at the same time.

This technology is challenging to appreciate without seeing a TBM in operation. A key takeaway is that TBMs are engineering marvels, that handle a variety of soil situations and different environments – from underwater to under cities.

TBM and tunnel-related losses

The advent of tunnel boring machines ushered an era of tunneling through complex geographies and geologies. While the end result yields credibility and excitement both for the entity that bored and the local government that initiated the project, the road from project planning to completion is riddled with risk. As a result, insurance for boring projects has proven to be a risky business as revealed by the frequency of major losses.

Perils

- Earthquakes
- Flooding of the tunnel from adits (passages leading into the mine for access or drainage)
- Fire spreading from the TBM or other equipment (construction transport vehicles, transformers)
- Collapses due to improper design, material, workmanship or unexpected geological conditions such as a front collapse or chimney. A chimney collapse is a cylindrical failure that might reach the surface and create a sinkhole under unfavorable conditions
- Deformations (squeezing, cracking of lining, etc.)
- Internal breakdown of TBMs (main bearing, gear boxes, etc.)
- Losses to TBM due to external obstacles found during excavation

Based on the examples shown in Table 1.0 on page 4, we can see that tunnel losses appear less likely to occur as a result of boring equipment, when the equipment is properly maintained and operated as designed. Insufficient or inaccurate data pertaining to the geology that will be bored through presents a major risk. Unfortunately, improper design and construction defects represent most of the losses, which translates to human omission and mistakes.

The perfect storm

In 2013, Hitachi Zosen Sakai Works delivered Bertha, at the time the world’s largest tunnel boring machine named after Seattle’s only female mayor, Bertha Landes. Three days after the TBM started the $1.35 billion boring project, Bertha ground to a halt. An investigation revealed that its seals and bearings were damaged from overheating. Recovery efforts led to $500 million in additional costs, and repairs took two years to complete. While the added costs and repair timeline made headlines, the rest of the story is far more intriguing.

Two lawsuits were filed as a result of the events that led up to Bertha’s breakdown. The contractor that was retained to bore the tunnels sued their insurance carrier, and the insurance carrier counter sued the contractor and the manufacturer of the boring machine.

Table 1.0 – Examples of tunnel losses (the list is not exhaustive)

Year	Project name & location	Peril	Cause	Cost US $
1994	Heathrow Express Link, London, UK	Collapse	Construction defect	141 million
1994	Great Belt Link, Denmark – Sweden	Fire	Cause of ignition unknown. Hydraulic fluid leak from a TBM was the primary fuel	33 million
1994	Gerat Belt Link, Denmark – Sweden	Flood	Seabed gave way	34 million
1994	Munich Metro, Germany	Collapse	Improper design	4 million
1994	Taipei metro, Taiwan	Collapse	Construction defect	12 million
1995	Taipei metro, Taiwan	Collapse	Construction defect	29 million
1995	Los Angeles metro, USA	Collapse	Engineers deviated from standard practice by planning the realignment of the tunnel without adequate supports	9 million
1999	Bolu tunnel, Anatolian Motorway, Turkey	Collapse	Earthquake / improper design	115 million
1999	Hull Yorkshire Tunnel, UK	Collapse	Improper design	55 million
1999	TAV tunnel Bologna-Florence, Italy	Collapse	Improper design / construction defect	9 million
2000	Taegu metro, South Korea	Collapse	Improper design	24 million
2000	Porto metro, Portugal	Collapse	Over excavation	Unknown
2001	Porto metro, Portugal	Collapse	Over excavation	Unknown
2002	Autoroute A86 – Socatop tunnel, Paris, France	Fire	Fire in a TBM construction transport vehicle	8 million
2002	Taiwan high speed railway	Collapse	Unknown	30 million
2003	Shanghai metro, China	Collapse	Improper design	80 million
2004	Singapore metro, Singapore	Collapse	Construction defect	Unknown
2005	Kaohsiung metro, Taiwan	Collapse	Construction defect	Unknown
2005	Barcelona metro, Spain	Collapse	Construction defect	Unknown
2005	Lausanne metro, Switzerland	Collapse	Construction defect	Unknown
2005	Lane Cove tunnel, Sydney, Australia	Collapse	Construction defect	Unknown
2009	Cologne metro, Germany	Collapse	Improper design / construction defect	Unknown
2009	Cairo metro, Egypt	Collapse	Improper design / construction defect	Unknown
2012	Istanbul high speed railway, Turkey	Collapse	Improper design / construction defect	29 million
2012	NYC Harbor Siphons project, USA	Flood	Hurricane storm surge flooding	Unknown
2015	Doha metro red line, Qatar	Flood	TBM hits pocket of underground water	Unknown

Pictured is a pit that was dug to perform repairs on Bertha.

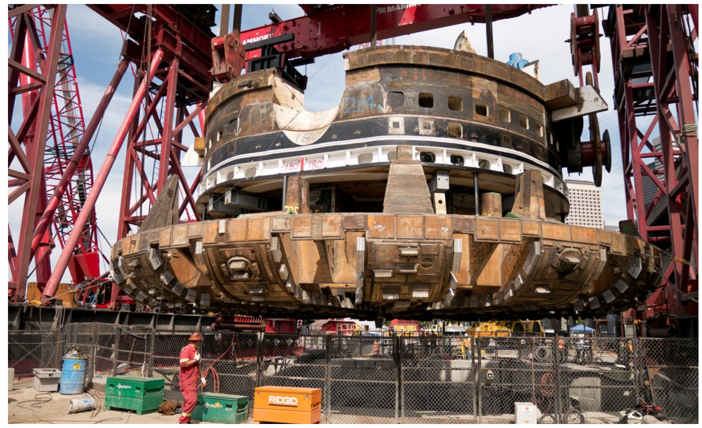
Bertha's problems began when the TBM hit a 120-foot-long, 8-inch-diameter steel well casing. Casing is a tubular structure that is placed in a drilled well to maintain the well opening. The casing also holds back unstable earth materials, preventing them from collapsing into the well. Some experts opined that Bertha was not powerful enough, until Hitachi Zosen made some modifications during the shutdown. Seattle Business Magazine published the firsthand experience of two workers who adamantly disagreed with allegations that Bertha was underpowered and too large to control.

The two workers described the events that led to Bertha's breakdown. While boring, operators noticed 3 to 4-foot pieces of pipe on the conveyor belt video feed. The conveyor moves debris out of the tunnel as the TBM progresses. The operators were not concerned; but then noticed larger than expected boulders showing up on the conveyor belt. At that point, Bertha was not progressing as quickly as the operators needed her to. It was evident that the TBM was experiencing some serious problems.

Since Bertha was having troubles progressing, rather than stopping and diagnosing the source of the problem(s), operators decided to push the TBM beyond its specified operational parameters. Bertha was designed to handle a thrust of 100,000 kilonewtons.

The operators increased Bertha's thrust to 325,000 kilonewtons, over three times the maximum specified. To put this in perspective, this thrust is approximately 9 times greater than the thrust required to launch a space shuttle. The TBM began to overheat and a safety feature automatically shut it down to protect its critical seals and bearings. Once cooled, the operators pushed Bertha again and again; it is believed that the cycled overheating is what damaged the TBM so severely.

There are a couple of additional points that offer another perspective. The operators were cognizant that Bertha was still under warranty. As such, they were not concerned about breaking the machine. Stopping the machine and checking what was wrong could have taken a week or two – precious time that would reduce the chance the contractor would earn the incentives built into the contract for early completion.



Pictured is Bertha's repaired cutterhead before it is lowered back into the pit.

The company contracted to bore the tunnel initially sought more than $600 million in payments for the delay. A judge limited the case to $300 million. At the end, not only did the contractor lose its claim, but they were ordered to pay the Washington State Department of Transportation (WSDOT) $57.2 million. Recently, a three-member appellate panel reversed a portion of the ruling that dismissed many of the claims in the lawsuit filed by the contractor and the WSDOT against a group of insurers that issued a builder's risk policy. It will be up to a jury now to decide what caused Bertha's breakdown.

As it pertains to this commentary, multiple factors contributed to this unfortunate scenario. The contractor claimed that WSDOT did not properly disclose that the well casing was made of steel. The tunnel boring machine had issues or required some modifications that were made by the manufacturer during the shutdown. The contractor was far more aggressive with the equipment because they were within the manufacturer's warranty period and early completion payments incentivized them to do so.

Guidelines for risk management of tunnel works

In the late 1990s, the tunnelling industry's reputation was suffering as a result of high-profile incidents all over the world. In 2002, the British Tunneling Society (BTS) was advised by the Association of British Insurers (ABI), of their intent to stop underwriting coverage for tunnel projects until something could be done to lower loss ratios.

Insurance company Munich Re summarized the consequences for the insurance industry as follows:

- High frequency of major tunnel losses.
- Insufficient premium income to pay for all the losses.
- Wide scope of cover indemnifies far beyond repair costs.
- Repair costs exceeding original construction costs.
- Insurance was “cheapest risk management tool”.
- Tunneling insurance notoriously unprofitable business.

In response to fears that insurance for tunnel projects would become unavailable, or far too expensive to secure, BTS and ABI joined forces to create a new benchmark for industry best practices. A code of practice for international risk management, or tunnel code of practice (TCOP), was published in 2006 and a 2nd revision in 2012. The TCOP was intended to serve as a project management tool to promote best practices in risk management and reduce the occurrence of accidents.

Unfortunately, major tunnel losses continued occurring with an unreduced frequency, even after the introduction of the code and the subsequent revision. Insurers still agreed that development of the code was an important step in building confidence in tunneling projects. "It has led to tunneling projects being more insurable today," explains Cedric Wong, senior engineering underwriter and vice president of projects and global markets at Swiss Re Corporate Solutions. "It doesn't guarantee success, but it gives the best possible chance of a successful outcome if it is followed and implemented. When we are presented with a tunnelling project by a broker, we look at the information provided by the client, contractor and we benchmark it against the TCOP," he says. "We can assess if they have taken a risk based approach in choosing the original tunnel alignment, have they procured based on both quality and cost, have established a risk management framework, are they using risk registers, have they got design checkers? We assess the project and if it aligns with the code and if we determine that risk management is solid, there is a good chance of insurability."

By 2018 it was a different story. "It is a good time for tunnel projects to buy insurance. With interest rates and return on investment at all time low, capital is flooding into the insurance sector as it produces good returns on equity in comparison to other investment options." said Wong.

Post-loss considerations

Damage inspections are performed following natural disasters or activities that accidently damage the tunnel. As noted above, damage may occur as a result of motor vehicle impact, fire, flood, earthquake, construction defect or explosion. When severe damage occurs, the tunnel should be closed until experts complete documenting the scene, evidence is secured, the damage is fixed, and the tunnel is deemed safe. Structural, environmental and equipment analysis should be performed, and emergency repairs may be needed.

Safety is of paramount importance. Devices such as breathing apparatus, protective clothing, and specialized equipment may be necessary. Inspection work should be coordinated with carriers, local authorities and emergency responders.

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Get in touch with an expert

Ignacio Sandoval
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