

Notes from Under- ground

Story by Jim Duffy

Tunnels are indispensable to our modern networks of trade, commerce and transportation. From ancient times to the modern day, the hard work of building them has involved some remarkable engineering achievements.

It's easy to take tunnels for granted. They're such an everyday part of modern life, allowing people and goods to move through mountains and under water in cars, trucks, trains and subways. But as anyone who has ever worked on a tunnel construction project knows, building safe and functional passages underwater or underground is a highly complex affair, requiring both the brute force of heavy construction machinery and the pinpoint precision available through high-tech survey and geological equipment.



Ancient Tunneling

It's not a job for amateurs unschooled in the ways of modern science. So put yourself in the sandals of Eupalinos, the enterprising Greek engineer who lived on the island of Samos in the sixth century B.C. Ruled by the notorious tyrant Polycrates, the island featured an imposing fortress, easy to defend save for one glaring weakness —the possibility that a long siege might succeed if enemies were able to cut off the supply of inland fresh water to the island's populated coastline.

Polycrates assigned Eupalinos to fix this homeland security glitch. The problem was, the solution involved digging a 4,000-foot-long conduit straight through a mountain of solid limestone. Eupalinos had to tackle this job without surveying instruments, magnetic compasses and topographic maps. Needless to say, explosives and power tools were not at hand. In fact, his ancient world didn't even have much in the way of basic mathematics.

It sounds like mission impossible, and yet the Tunnel of Eupalinos is there on Samos for tourists to see today. It's not the world's first tunnel, considering that Egyptians and Babylonians had dug out earlier ones. But there is an air of mystery about Eupalinos' tunnel; it's been a source of great fascination for scientists and historians over the centuries.

Engineering Mystery

"No one knows exactly how he did it," concedes Tom Apostol, a retired mathematician from Caltech. Apostol is among the small army of modern-day minds who've tried to figure out how Eupalinos might have managed to establish and maintain a straight line that could be followed underground through solid rock by two crews working from opposite ends of the project while keeping to a precise elevation at all times. Numerous scientists have tried and failed over the centuries to put aside their modern tools and replicate the level of precision Eupalinos achieved.

Apostol and a Caltech colleague, Mamikon Mnatsakanian, have offered a new possible solution. In a 2004 article for *Engineering & Science*, a quarterly magazine put out by Caltech, they propose that Eupalinos erected a 23-foot-tall tower atop the mountain he was tunneling through in order to gain clear sight lines in both directions down to the sea. With that perspective on his elevation, he could have used a simple sighting tool that consists basically of a pair of 2-meter poles with thin, equally weighted strings attached to the ends.

Taking careful measures along one small segment at a time, this strategy theoretically would achieve something approaching the precision of Eupalinos' tunnel. In the end, at the point where his two crews of enslaved workers met,



The Tunnel of Eupalinos on the Greek Island of Samos, above, is an ancient engineering marvel, spanning more than 1,200 meters (4,000 feet) through the island's mountains.

they were within just 23 inches of each other in elevation.

"This represents an engineering achievement of the first magnitude," Apostol writes.

Digging Big

Needless to say, modern-day tunneling works a little bit differently than it did when Eupalinos pulled off the feat that made him famous. But that doesn't mean that ingenuity and creativity aren't still the keys to meeting the engineering challenges at hand. Consider the case of Boston's \$15 billion Big Dig project. Now mostly completed, the controversial project was undertaken in the late 1980s in response to a civic conundrum of the first order. The city's Central Artery, an elevated six-lane highway that was then 30 years old, had become one of the United States' most clogged and dangerous roadways. Traffic projections for 2010 envisioned tie-ups lasting 16 hours every weekday. Similar problems plagued a pair of tunnels under the Boston Harbor. The solution involved replacing the Central Artery with an eight- to 10-lane underground highway directly below the old elevated route and adding a new four-lane tunnel under South Boston and the Boston Harbor to link city traffic with Logan International Airport.

Actual construction work on the Big Dig stretched on for 15 years, and the project was mired in controversy for



Troubles on the Big Dig

Boston's Big Dig has been dogged by criticism and controversy almost from the first day of construction. Initial projections put a \$2.6 billion price tag on the project, but the final cost came in at more than five times that amount, nearly \$15 billion. The state of Massachusetts has filed several lawsuits in recent years against contractors over these cost overruns.

The controversies multiplied once the Big Dig actually opened to traffic. In early 2004, icy road conditions forced the temporary closure of one new tunnel. A few months later, gushing water forced the temporary closure of another.

This past July, the Big Dig's problems took a tragic turn when concrete ceiling tiles collapsed in the Ted Williams Tunnel on Interstate 90, killing a 38-year-old woman traveling with her husband en route to Logan International

Airport. The accident sparked a project-wide safety examination that uncovered numerous problems with other ceiling tiles. The Massachusetts Turnpike Authority has estimated the bill for repairs will reach \$15 million.

In November, the Massachusetts Attorney General filed a multimillion dollar lawsuit charging a dozen different companies involved in management, construction, design, and oversight of the tunnel work with negligence. One of those companies, project manager Bechtel/Parsons Brinckerhoff, faces the more serious charge of gross negligence in the suit. In August, the family of the woman who died in the accident filed a wrongful death suit against many of the same companies. In addition, a grand jury has been convened to determine whether any companies or individuals will face criminal charges in the case.



Ways and Means

There are countless ways to build a tunnel. Among the most notable are:

- Cut and cover, in which a trench is dug then covered over with beams or other supports used to hold up the roof.
- Tunnel shields, in which excavation is advanced by pushing tube-shaped devices through underground surfaces cleared through blasting.
- Tunnel-boring machines, which automate the tunnel-digging process, are like giant drills with shield-shaped cylindrical tips.
- In the New Austrian tunneling method, the natural geological forces at work in rock and soil formations surrounding the project are carefully integrated into the design of a tunnel support structure.
- Immersed tubes are underwater tunneling's version of manufactured housing. Tunnel pieces constructed off site are dropped into a waterway and then welded together. The best-known American examples are New York's 63rd Street Tunnel and San Francisco's Transbay Tube.

much of that time (see sidebar page 11). The logistics of doing this job in the midst of a major city going about its daily business were mind-boggling. Perhaps the most daunting challenge of all was figuring out a way to keep the old elevated highway up and carrying nearly 200,000 vehicles a day while work crews dug an enormous hole in the ground directly below it.

That's why the Big Dig involved the largest use of slurry walls ever undertaken in North America. These are basically concrete walls that run from the ground down to bedrock. They take their name from the mix of clay and water that's pumped into a man-made trench to hold the sides of the walls in place until concrete is poured in. In Boston, clamshell excavators and continuous milling machines were employed to cut a 3-foot trench down to bedrock, which lies as far as 120 feet below the ground in some places. Reinforcing steel beams were dropped into the slurry-filled trench before concrete was poured in.

Completed in 10-foot-long segments—or “panels”—covering more than five miles in all, these would become the walls of the new underground Central Artery. But the slurry walls tackled two other tasks along the way. First, they produced a stable work area for excavation, something that would usually involve much wider, sloping slurry walls. Second, the entire weight of the old elevated highway was shifted onto them so that workers could remove the footings supporting the beams under the highway.

Another imposing challenge arose in downtown Boston at Dewey Square, where four lanes of a new underground roadway would have to pass under a subway tunnel. This crossing came at the lowest point of the Big Dig—120 feet below the surface. In addition, transit authorities were planning to add a new tunnel for an electric bus line serving Dewey Square. Slurry walls were out of the question this time, as it would have been impossible to cut one straight through a subway line and a tunnel. In addition, there was the issue of how to dig a tunnel in such a way that the subway line above it wouldn't settle and damage the train tracks. Here, the engineers employed a strategy called “underpinning,” supporting the subway by inserting underneath it a reinforced concrete table resting on bedrock.

The Big Dig encountered a different sort of problem while tunneling under the Fort Point Channel to create a nine-lane highway. In building the old Ted Williams Tunnel, Boston had successfully dropped steel tunnel sections—each longer than a football field—into an underwater trench. These sections were barged into Boston by water, but a pair of existing bridges en route to Fort Point hang too low over the water for such barges to get through.

Here, Big Dig engineers opted for something that had

never been tried in the United States before—concrete tunnel sections. Because these sections had to be fabricated close to the site to avoid the problem with the bridges, Big Dig engineers decided to build their own “casting basin.” They excavated some 450,000 cubic yards of dirt to make a dry dock area big enough to hold an aircraft carrier—1,000 feet long, 300 feet wide and 60 feet deep.

Much of this dry dock actually sat below the waterline inside the channel, but the work area was kept dry by the construction of temporary watertight barriers, or cofferdams, filled with crushed stone. Once the tunnel sections were built, these cofferdams were removed, flooding the basin and allowing the tunnel sections to be floated out into the channel and then lowered into the trench. All 27 feet high, the sections were as long as 414 feet and as wide as 174 feet apiece. The heaviest weighed more than 50,000 tons.

That’s a lot of weight, considering that the city’s Red Line subway runs under the new tunnel. Here, Big Dig planners opted to drill 110 concrete shafts down as much as 145 feet into bedrock. The plan was to keep weight off the subway by sitting the tunnel on the shafts. The first few tunnel sections were floated out early in the year 2000. Then the cofferdams were reinstalled and the casting basin reopened so that more sections could be built. The last two sections were dropped in June of 2001.

First envisioned in the early 1800s, the Thames Tunnel, below, took more than 18 years to build using tunnel shields.

Long-term Plans

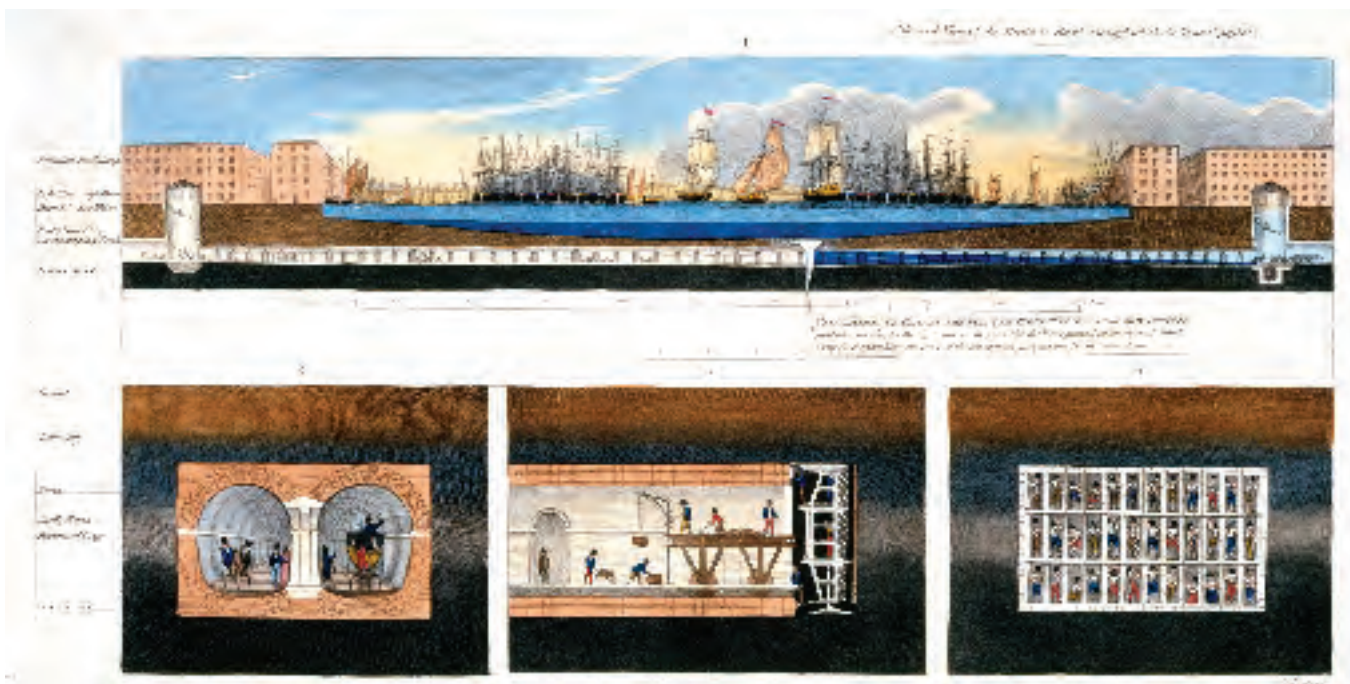
In the works for two decades now, the Big Dig seems a never-ending affair to many Bostonians. But judging by historical standards of tunnel building, it hasn’t taken that long. It was back in the early 1800s when British engineer Mark Isambard Brunel decided that the time had come to carve a route for pedestrians and carriages to cross under the Thames River in London.

Brunel wasn’t the first to propose such a project, but he was without a doubt the first to gain his key moment of inspiration for how to accomplish it while studying a tiny shipworm bore into an oak plank.

These creatures were what inspired him to create the first “tunnel shield.” Powered by the muscles of workingmen, Brunel’s version of the shield looked like a giant tin can with one end removed altogether and the other end punctured with a small hole. The shield went into service in 1825 on what was supposed to be a three-year project. Opening ceremonies were actually held 18 years later, after all manner of leaks, collapses and other delays.

To make matters worse, the Thames Tunnel was a financial bust at first, in part because the city declined to put in proper entrance and exit routes for carriages, leaving only penny-a-head pedestrians as paying customers. But, eventually, in 1865, it became part of the London Underground and remains in service today.

As impressive as Brunel’s achievement was, it pales next to another 19th-century job—the Mont-Cenis Tunnel through the Alps at the border between Italy and France. The project



was unprecedented: blasting and digging a seven-mile hole through the base of a mountain. Early estimates put the likely time frame of the job at 40 years, but the work picked up pace soon after its 1857 inception thanks to three inventions.

First, University of Geneva scientist Daniel Colladon came up with a way to effectively transport steam power deep into a tunnel, opening up the possibility of mechanical drills. Then, such a drill was actually developed by a team led by Germain Sommeiller, who went on to become the chief engineer on the Mont-Cenis project.

The third major breakthrough came courtesy of the Swedish chemist Alfred Nobel and his discoveries about using nitroglycerin as a blasting agent. The arrival of dynamite meant that fewer and smaller blasting holes needed to be drilled than with the old black gunpowder. In addition, dynamite creates much less smoke than powder, a boon to workers who previously could barely see where they were working amid the dark haze that hung, constantly, in the tunnel.

Two crews worked from opposite ends of the tunnel, meeting 13 years later, on December 26, 1870. Tragically, the engineers on the first three trains that tried to run through the tunnel's incline were overcome by fumes created by their own steam engines—two died of asphyxiation. This crisis was

solved with the arrival of imported “smoke-consuming” engines developed for the London Underground, and the tunnel formally opened in September 1871.

Also called the Frejus Rail Tunnel, the route through Mont-Cenis was twice as long as any other tunnel in the world on the day it opened. Obviously, this represents something other than an incremental advance in human achievement. Slow and steady isn't always how things go in engineering and tunneling. Whether in ancient Greece, industrial Europe or modern-day America, dramatic advances can come in sudden and surprising bursts. You never know what's going to happen when engineers get together with construction teams to solve a problem that's never been solved before.

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Crossing the Channel at Last

The Channel Tunnel connecting England and France is probably the world's most famous tunnel, even if its renown isn't related to any notable engineering feats. As the historian Joseph Gies has pointed out, building the “Chunnel” was in some ways an easier job than getting under the Hudson River in New York City.

But the Channel Tunnel's completion in 1994 represented the realization of a dream that had captured human imaginations for centuries. The first proposal to make a passable route under the English Channel dates to 1802 and was followed by countless other plans.

Some of these were downright

silly—one envisioned a picket-fence-like row of vents rising out of the sea to feed fresh air down into the tunnel. But many others were workable designs that fell victim to political or financial complications. France and England finally agreed to undertake the project in 1984.

Over the next decade, some 15,000 workers tackled the work of building three tunnels, two for trains and one for maintenance. Eleven tunnel-boring machines were used in the work, each serving as a sort of mobile excavation factory able to drill holes and remove debris. In all, more than 10 million cubic yards of soil were removed from the bottom of the Channel.

The maintenance passage was the first of the tunnels completed. When British and French crews working from opposite shores and employing the latest in laser survey techniques met on May 22, 1991, the centerlines of the two sides of this tunnel were separated by just 14.1 inches horizontally and 2.3 inches vertically.

Tunnels By the Numbers:

The **Seikan Tunnel**, the world's longest, is a rail route that links the Japanese islands of Honshu and Hokkaido under the Tsugaru Strait over a distance of 33.5 miles—two miles longer than the Channel Tunnel between England and France. Construction at Seikan began in 1971 in response to dire forecasts of traffic levels expected to overwhelm an existing ferry system. Completed in 1985, Seikan is widely regarded as an engineering marvel, but those forecasts were off the mark. Only 1.7 million passengers travel the tunnel every year—less than the old ferry system once served. The project cost \$3.6 billion.

The **Gotthard Base Tunnel** now being built in Switzerland for railroad traffic will extend for 36 miles under the Alps. It's scheduled for completion in 2015.

China's just-finished **Wushaoling Tunnel** is the sixth longest rail tunnel in the world, at nearly 13 miles.

The longest tunnel in North America is the 9-mile-long **Mount Macdonald Tunnel** through the Selkirk Mountains in the Canadian Province of British Columbia.

Though it's only 1.5 miles long, the **Lincoln Tunnel** under the Hudson River between New York and New Jersey ranks among the world's busiest vehicular tunnels, carrying 120,000 cars and trucks a day. It was among the targets eyed by Islamic terrorists in a failed 1993 plot to destroy a series of New York City landmarks.

The longest vehicular tunnel in the world is the **Laerdal** in Aurland, Norway, at 15 miles.

Upon its completion, currently scheduled for 2007, China's **Zhongnanshan Tunnel** will move into second place for vehicular tunnels at 11.2 miles.