Tunnel Surveying and Deformation Monitoring

3 Hours

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Final Exam

1. What does the term “TBM” stand for?
   a. Tunnel boring machine
   b. Tunnel blaze machine
   c. Temporary boring machine
   d. The boring machine

2. What type of rock were ants found in 92 million years ago?
   a. Diamonds
   b. Rubies
   c. Baltic Amber
   d. Jasper

3. What type of chambers were in the Great pyramid?
   a. King and Queen
   b. Mummy
   c. Dogs
   d. Cats

4. The English Channel Tunnel was also called?
   a. Euro Tunnel
   b. French Tunnel
   c. English Tunnel
   d. European Transport

5. What is the minimum control points required on each end of the tunnel?
   a. One
   b. Two
   c. Three
   d. Zero

6. What measurement should you have off the centerline if you have 8 feet diameter tunnel when measuring the shield?
   a. Ten feet
   b. Eight feet
   c. Nine feet
   d. Four feet
7. The Seikan tunnel is located where?
   a. China
   b. Japan
   c. United State
   d. Korea

8. When was liquid shotcrete invented?
   a. 1907
   b. 2000
   c. 2010
   d. 2018

9. The Port of Miami Tunnel is an example of?
   a. TBM Surveyed tunnel
   b. Cut and Cover
   c. Drill and Blast Tunnel
   d. Open Pit

10. How long was the Michigan Ditch Tunnel?
    a. 450 feet
    b. 968 feet
    c. 1450 feet
    d. 766 feet
Introduction to Tunnel Surveying and Deformation Monitoring

History of Tunneling

A tunnel is an underground passageway through a mountain, hill, building, road or waterway to establish access on both sides. Well before we started digging them, many different creatures built and used tunnels in one way or another. Some of the earliest and most fascinating tunnelers are ants. Samples of a mineral called Baltic amber, with ants encased, help us date them back to 92 million years old.

Ants use elaborate pathways through the earth to transport food and water and also to build colonies underground that were protected from the elements. The tunnels built by ants are multi-level and very complex for such small animals. It’s thought that one anthill can take up to 15 years to create, so the tunnels underneath would not be easy projects. The worker ants don’t have a particularly long lifespan, but the queen can live for over 10 years, giving it one of the longest lifecycles of any insect. These colonies also featured drones that would try to impregnate neighboring queens.

Besides building tunnels, ants have contributed greatly to our understanding of agriculture, communication and community. “Ants, just like any species of animal, fit into a much larger ecosystem, which they are a vital part. Without ants, which form a steady base to many ecosystems, some habitats would likely fail to thrive. In fact a great many may fail to thrive, seeing as ants are such an enormous force. They till the soil, dispose of the dead and rotting, weed out the slow and the weak (in the case of soldier ants for example,) create habitats where other insect species are dependent on, and provide food for many thousands of species of animals.” (1)

Tunnels (both human and machine dug) have been around for thousands of years and the technology has greatly increased over time. For example, the ancient Egyptians used tunnels for many different purposes. The Giza Water Tunnels are thought to have been built as an elaborate system for water to travel back and forth between ancient Egyptian colonies. Some believe that this water system could have been constructed prior to the actual pyramids and could also have been built to generate power through water. Many others believe the earliest human dug tunnels are under the Great Pyramid, including elaborate pathways and waterways. Like the Giza Water Tunnels, the shaft at the bottom of the Great Pyramid may have been built to generate energy from the storage of water as well. The tunnels under Egypt and some of the other pyramids are also thought to have been used for travel, as a type of on-foot underground subway system.
Pictured above is the Great Pyramid’s tunnel system showing an entrance with a descending passageway to a subterranean chamber. These passageways depicted here may be the earliest tunnels mankind has ever created and inhabited. Two of the upper tunnels are shown to be open which would establish a lighting system for the King’s Chamber, Queen’s Chamber and Grand Gallery.

Some believe these tunnels were a gateway to another dimension or a so-called underworld.

“What’s interesting about Lake Moeris and Hawara, in Egypt is that it shows a massive network of tunnels and underground waterways as well. The Greek historian Herodotus wrote about the “pathways” between the Labyrinth of Hawara and the Giza Plateau being linked, much like an ancient underground subway system.

“If Hawara has Twelve Great Halls, as the ancient Greeks wrote about, the water tunnels under the Great Pyramid may be even more significant. Before a Pharaoh could face the trials of the Twelve Great Halls, he first had to secure passage in the form of a boat that would carry him down the river of the Underworld. Once a Pharaoh was placed in his tomb, his spirit would descend into the Underworld where he would meet with a group of guardians and the gods Heka, Sia, and Hu who would help him (along with the god, Sobek) during his journey. The Pharaoh would then set sail and begin his adventure.

“The water tunnels under the Giza Plateau may also have a dual purpose in carrying out ritual enactments on the journey to the Underworld. The second level of the Osiris Shaft may be the symbolic sarcophagi of the seven “guardians” and the third level the ascension portal to the Underworld.” (2)

The construction of these tunnels are elaborate, and some of the mathematics behind how they were constructed is thought to be beyond the abilities of ancient humanity. Many theories and beliefs exist about these tunnels and the construction methods, but nothing has been scientifically proven. That said, the method the Egyptians used to build these underground tunnels is thought to fall under the “cut
and cover method,” in which the tunnel and shaft are dug and then reinforced after to protect the shaft of the tunnel. It is highly likely that these tunnels were built using hand tools of the era and took several thousands of years to create and establish a method of protecting them after construction.

The next known civilizations to create tunnels were the Babylonians and the Persians around 3,000 years ago. This is when some of the first bridges also date back to. These architects designed huge underground networks known as quant or kareez. These tunnels were thought to have been used mainly for irrigation purposes.

“These irrigation tunnels were used to transport water underground through deserts which enabled life in some of the most hostile lands on planet earth (Iranian city of Gonabad still has a working network of kareez tunnels that is 2700 year old). In Babylonia, royal families enjoyed fresh water from Euphrates that was delivered to them through an incredibly built 900m long tunnel that was lined with bricks.” (3)

The Romans then adopted techniques for building tunnels in different territories such as Europe, North Africa and Asia. The tunnels the Romans built were used for many things such as water transportation, river diversion and to drain lakes for the irrigation of farm lands, as well as for their road and mining operations at the time. The Romans developed a qanat technique for the process of building their tunnels.

“The Etruscans adopted the qanat technique in the 6th century BCE to build a large number of water-supply tunnels called cuniculi in the northeast of Rome. They later passed on their know-how to the Romans who also used the qanat method to construct aqueducts. Vitruvius in his On Architecture describes how Roman qanat tunnels were constructed with vertical shafts (called puteus or lumen) dug at 35.5 m (115 ft) intervals, even though in reality intervals could vary between 30 m (98 ft) to 60 m (197 ft). The shafts were equipped with handholds and footholds and were covered with wooden or stone lids. To ensure that the shafts were vertical, Romans hung plumb-bob lines from a rod across the top and made sure that the bob ended in the center down the shaft. Plumb bob lines were also used to measure the depth of the shaft and to determine the slope of the tunnel with precision. Qanat tunnels were similarly built to divert rivers and drain lakes for agriculture and/or to regulate water levels. For example, Emperor Claudius built the 5.6 km (3.5 miles) long Claudius tunnel in 41 CE to drain the Fucine Lake (Lacus Fucinus). This tunnel had shafts that were up to 122 m deep, took 11 years to build and used approximately 30,000 workers.” (4)

The Romans were the first to develop counter-excavation tunnels where the tunnel was basically dug from each side and met close to the middle. This method was typically used in mountainous areas where they were unable to use the qanat technique. This new method required a greater understanding of surveying and geology. Geometry became a tool they used to make sure the tunnel would line up correctly in the middle. A lot of this was done by looking at the angle of the light which penetrated the entrance and exit of the tunnel. Two typical errors would occur: altimetric (related to the altitude) or planimetric (horizontal errors in measurement). The worst of the two was altimetric as it would often result in one side not being useable.
“The Saldae aqueduct system (in modern day Bejaia, Algeria) built by the Romans in circa 150 CE and consisting of a 300 m (984 ft) bridge and a 428 m (1,404 ft) tunnel is known for an inscription on a three-sided semi-column written by the surveyor Nonius Danus. The inscription provides unique technical details about the construction of the tunnel of Saldae and the problems faced by the builders. Nonius Danus describes how the two teams of builders missed each other in the mountain and how the later construction of a lateral link between the two galleries corrected the initial error. In this instance, the error was planimetric and could be rectified.” (4)

When the Romans encountered topographical areas such as hills or mountains that were too high or steep to pass, they dug tunnels for their roads. One key example is the Furlo Pass tunnel, which was 121 feet long and 20 feet high. This was built in 69-79 AD by emperor Vespian using the counter-excavation method. Also, the Cocceius tunnel built in 38-36 BC shows the first time ventilation shafts were built. This tunnel was well decorated with statues set in the Avernus side.

The Romans were also building tunnels at this time to extract gold and other precious minerals. Once a vein was located, shafts and tunnels were dug to bring this material to the surface. These tunnels required less planning because the sole purpose was to extract the mineral so they would follow the vein.

“Roman tunnel projects were usually planned by a military librarian (surveyor) and built by military personnel often helped by a number of slaves. The length of construction of the tunnel
depended on the method being used and the type of rock being excavated. The *qanat* construction method was usually faster than the counter-excavation as it was more straightforward and because the mountain could be excavated not only from the tunnel mouths but also from shafts. Lack of ventilation, especially for long tunnels without shafts, was also an issue, and made construction work exhausting for tunnel workers. The type of rock could also influence construction times. When the rock was hard, Romans employed a technique called fire-quenching which consisted of heating the rock with fire, and then suddenly cooling it with cold water so that it would crack. Progress through hard rock could be very slow and it was not uncommon for tunnels to take years if not decades to be built. Construction marks left on a Roman tunnel in Bologna shows us that the rate of advance through solid rock was 30 cm (12 inches) per day. In contrast, the rate of advance of the Claudius tunnel can be calculated at 1.4 m (55 inches) per day.” (4)

The Romans also were pioneers in maintaining their tunnels. The tunnels would get full of debris and leaks would appear, which was dangerous because it could jeopardize the overall integrity of the tunnel walls and cause cave-ins. Constructed shafts were used to alleviate air pressure in water tunnels and this aided in the flow of the water. The Romans often etched inscriptions inside the tunnel of the architect or surveyor that was responsible for the work.

“Just as with other large construction projects, tunnels were a way for emperors to not only show their benevolence but also to project their power throughout the empire. Tunnels were built in the territories that Rome controlled in Europe, North Africa and Asia Minor in order to transport water, to irrigate agricultural lands, for roads and for mining activities. The Romans adopted the *qanat* construction method invented by the Persians and by the 6th century BCE they also mastered the counter-excavation method to pierce through high mountains. Tunnels could take years to be built and needed to be regularly maintained. Even though they are not as visible as other large ancient construction projects, be they aqueducts, bridges or viaducts, Roman tunnels truly are engineering marvels and a testament to the Romans’ great engineering skills.” (4)
The Romans, like the Egyptians, also built elaborate maze-like tunnels and quarries under the streets and buildings. These were discovered when the streets above began collapsing into quarries below. Rome was built in an area that was created by volcanism meaning the area contained a lot of volcanic rocks that were easily converted into building blocks. These tunnels suffered from long term sustainability because when the rock was exposed to air it would weather. Also, they would continue to widen these tunnels and create new structures above them compromising the integrity.

These tunnels were used for bomb shelters during World War 2 and provided safety from overhead attacks. They were also used for mushroom farming and as sewage systems. In recent times, city officials are pouring mortar into the tunnels to fix critical areas that are a danger of cave-ins.

On the island of Samos, the Greeks built the Tunnel of Eupalinos, which is known as one of the greatest engineering achievements of the classic world. This tunnel functioned as an aqueduct which is a conduit for water that typically carries a large quantity of it. The calculations and mathematics used to construct this tunnel are said to be on par with modern day engineers.

“The Tunnel of Eupalinos was a project conceived during the 6th century BC. During this time, the ancient town of Samos, now known as Pythagorio / Pythagoreio / Pythagorion, was experiencing a period of prosperity. Along with this growing wealth, the town also saw an increase in the size of its population. Unfortunately, water sources in the town were not enough to satisfy the needs of its people. To maintain the prosperity of his town, the tyrant Polykrates had to find a solution to this problem, and employed the engineer Eupalinos of Megara to build an aqueduct. Little is known about Eupalinos today. It is said that he was the son of a man by the name of Naustraphos, and came from a place known as Megara, which is situated between Corinth and Athens. The aqueduct was not the first project that Eupalinos had worked on under Polykrates. It has been recorded that, prior to this, Eupalinos was also commissioned to build the cyclopean wall that surrounded the town of Samos, as well as the mole in its harbor.”(S)

In 1681, for the first time, France used gunpowder to blast the tunnels for a 515 feet long Royal Canal in Laguedoc - this was one of the first major advances beyond hand digging. Gunpowder rapidly grew as a key method to blast tunnels like the long (160-m) tunnel in France. Nearing 1850, further advances arose in the field of tunneling. The chemical compound nitroglycerine (dynamite) replaced the less force-breeding agent of black (gun) powder in tunnel blasting. Steam and compressed air were also implemented in power drills to create holes for the explosive charges. The mechanized approaches to tunneling eventually replaced the hang-digging labor-intensive forms of earlier tunneling.

In the early-to-mid 19th century, Marc Brunel and his son developed several methods of tunneling shields that enabled them, alongside James Greathead, to construct two tunnels under the Thames River near London. The shield enclosure was divided into several horizontal and vertical compartments. During tunneling, a worker in each compartment could remove one plank at a time, dig a short length and replace a plank for continuous construction. Once the individual space was dug from the front surface, the shield as a whole was pushed forward for advancement.

Later in the 19th century, American tunnel constructors took on one of the major risks of tunneling: water. Clinton Haskins successfully kept water from getting into a railroad tunnel by filling it with compressed air. This technique is still employed in some cases today but only when workers are allowed to spend time in decompression chambers after working. The technique poses great risks.
because allowing workers to have required decompression chambers would limit emergency exits. The pressure within the tunnel must also be carefully monitored - it is critical to balance with the surrounding earth and water pressure to ensure the tunnel does not collapse or burst. (6)

The 20th century brought about significant changes in traditional tunneling methods and technology. In 1907, a liquid concrete called shotcrete was invented to be sprayed on surfaces of the tunnel for preliminary and final lining. Shotcrete - varying by ground conditions and specific needs of tunnel - is a three material compound: cement, aggregate and water. Sprayed concrete quickly became the preferred material for lining tunnels because it is very important for stabilizing the excavated tunnel section. Now, modern tunneling is almost inconceivable without sprayed shotcrete. The complete technology can be defined as the material (sprayed concrete), the sprayed concreting process and the sprayed concrete system. (7) This long tradition and its more recent developments allow for knowing the exact finished grade inside (elevation) to the millimeter, thus making it easier to survey as well as ensuring its stability and managing risk. (8)

One of the most vital evolutions for tunneling technology and underground construction works was the TBM. James S. Robbins, while attempting to create innovative solutions for the challenges of underground projects, designed the modern tunnel-boring machine (TBM) for South Dakota’s Oahe Dam project.
In the early 20th century, tunnel constructors began to use stabilizing techniques for soft soil. One early method of stabilizing the soil was to freeze it by circulating coolant through pipes at various intervals throughout the to-be-tunnelled area. Similarly and still frequently used -from the 1970s on- for stabilizing and waterproofing is grout (liquid bonding) injection into the surrounding area (soil and fractured rock in the tunnel area).

The historical emphasis has often been about connecting the world's populations, improving accessibility to each other and resources, but tunnels have had other moments of significance. For example, a 1963 film, *The Great Escape*, based on a true story, portrayed prisoners escaping from a German POW camp by digging three tunnels they named Tom, Dick, and Harry.

In modern times, Switzerland has been known as an innovator and a pioneer in technology. In the 1960's they sought to address the debilitating gridlock of traffic that separated Eastern and Western Europe. The St. Gotthard Tunnel was constructed over a ten year period between 1970 and 1980. It became an addition to the existing A2 motorway to relieve the heavy traffic burdens through central Europe. With over 17,000 vehicles a day passing through the Swiss Alps, the tunnel has been witness to continued heavy traffic jams and incidences of fatal accidents often involving larger trucks. In response, the Swiss government has decided to build a second road tunnel through the Gotthard mountain range in an attempt to reduce traffic congestion in the existing one. The hope is to have the tunnel ready for use by 2027.

The advancement in tunneling and the modern world demanded greater and greater feats that once seemed impossible. Construction on the English Channel Tunnel between England and France, originally a dream for centuries envisioned and encouraged by Napoleon as the ethos of modern engineering, technology and the evolving industrialized world began in 1987. Then referred to as the Chunnel and now known as the Eurotunnel, it was completed in 1994 at a finished and final cost of $21 billion. The largest construction expenditure to-date, after 192 years of planning and 6 years of non-stop work, finally came to completion.

The rail tunnels for two-way traffic (north and south) and one service tunnel are each 31 mi (50 km) in length with an average depth of 150 ft (46 m) under the seabed. It is the first physical link between Britain and the European continent. Passenger rail service is provided, as well as a ferry for automobiles and trucks. Travel times from London to Paris have been significantly reduced (previously five hours or greater) over the sea (English Channel) to three hours because of the Eurotunnel. It has dramatically changed the economics and quality of life in both countries as well as across Europe.
Around the same time, the Seikan Tunnel in Japan was placed in service in 1988. The 33mi-
(53km) long tunnel connects the northern tip of Japan's main islands, passing under the Tsugaru Strait. The Seikan Tunnel is the world's longest submarine tunnel, involving excavation 330 ft (100 m) below the seabed across a strait where the sea is up to 460 ft (140 m) in depth. Japan's Seikan Tunnel, also the world's longest and deepest railway tunnel (787 feet below sea level), connects the islands of two critical economic areas - Honshu and Hokkaido.

In the summer of 1992, the Norwegian Parliament decided to take on one of the greatest construction projects ever imagined. They wanted to build the world’s largest road tunnel. The tunnel was to be 25 km long to connect the areas of Aurland and Laerdal for the new main highway that connected Oslo and Bergen. The two cities are international destinations as well as economic powerhouses for Norway. The level of reliability in transport due to mountainous areas with narrow roads and fjord crossings made it imperative to craft a lasting solution for connecting the two cities. The decision-making process was lengthy and it was debated to refurbish existing roads but the associated risk of the difficult and dangerous terrain was a strong weight in choosing to build a tunnel over alternative options. Here the environmental impact was carefully reviewed and the tunnel was seen as an investment of prosperity to avoid destroying the unspoiled natural landscape throughout the region.

This endeavor required an immense amount of technology to pull off. To determine the fixed survey points (the measurements on which all other measurements will be built upon) navigation
satellites were used to attain the highest precision possible. Once inside of the tunnel, laser beams indicated where the bearings were, thus allowing for a computer on the drilling jumbo to automatically position the drilling equipment according to the known patterns.

It was vital that the drilling and blasting work be carried out with extremely precise execution at 1000 meters under the mountain. The blasting was carried out by using 100 holes, 45-51mm in diameter and 5.2 meters deep for each blast. For the excavated materials, dump trucks used permanent roads in parallel with the tunneling works to dispose of the 2.5 million cubic meters of rock from the digging process. The removal of mined materials was one of the toughest challenges of this particular tunnel. This was because the Norwegian Public Roads Administration (NPRA) had to avoid the conflicts arising from the cultural importance of the landscape as well the productivity of agricultural land in the nearby valley. The resolution to this challenge was achieved by building more than half of the tunnel from a 2.1 km long access tunnel in Tynjadal - a side valley opening out 8km east of Laerdal. This allowed for the mined ground to be deposited while having no visible effect on the main valley as well as opposing no risk of hazardous run-off into the watercourses. (22)

Early on in the lifecycle of the project, NPRA faced design challenges. The administration wanted to design the tunnel to make sure the 20-minute-long trip wasn’t too monotonous. This was to ensure that drivers wouldn’t lose concentration during the long journey, both to manage the overall risk as well as the environmental and societal impact of the project. NPRA brought in an expert group of psychologists at SINTEF (the Industrial and Technological Research Association) to access and create a means of making the journey a pleasant and enjoyable one.

Due to the length of the tunnel, the ventilation was also a significant challenge. The tunnel requires a cleaning plant for the air that is located 10km from Aurland - it was installed in a short side tunnel. The air quality in the tunnel is continuously monitored and the system for cleaning automatically initiates whenever required; as does the electrostatic precipitator for de-dusting at predetermined regular intervals.

One of the biggest investments of this particular tunnel were the safety measures and equipment. A top priority is fire safety because of the length of the tunnel. Due to the tunnel going through dry rock, there was little need for sealing water seepage as well as flood risk. Even with these conditions addressed and managed, Norway spent millions of Kroners (currency of the time) on equipment for monitoring, ventilation system checks, radio connections, lighting, traffic lights and emergency equipment. This particular example can be seen as complex while there are often smaller feats going on with more regularity.

Expensive machinery and lengthy planning is not always necessary for tunnel excavation. Throughout history, people have had ambitions of their own to construct underground works. In 2005, Smugglers dug a 360-foot-long tunnel from a Quonset hut in Canada to the living room of a house in Lynden, Wash. Upon discovering this, police admire its lights, ventilation and concrete floor. This raises many questions - how many tunnels exist that are not of public knowledge and in what unique ways were they crafted? Is it safe to attempt to build and survey a tunnel for one’s self?
Massive and noteworthy tunnel projects are not limited to Europe and North America and they extend beyond the engineering mastery of Japan. China has taken on epic underground works of their own. The second longest road (twin-tube) tunnel, at 18.02 km in length, in the world is the Zhongnanshan Tunnel in China. The tunnel passes through the Qinling mountains in Shaanxi province of China. The $410 million dollar tunnel was built to connect (north-south) the highway between Baotou and Beihai. The tunnel consists of two tubes that allow four lanes of vehicular traffic. The tunnels, like Laerdal Tunnel, were bored using conventional drilling and blasting methods through gneiss and granite rock geology. After five years of construction, the tunnel was opened in January 2007.

Two years later, the Maijishan tunnel for the G30 Expressway was opened. Also a twin tube tunnel with four lanes, the Maijishan runs through the main ridge of the Qingling Mountain in the Gansu province. The 12,290m long tunnel ranks as the seventh longest road tunnel in the world and took four years to construct.

The Baojiashan tunnel - ranking tenth on the list of longest road tunnels in the world - was opened in May 2009. The 11.18 km long road tunnel is the third longest in China. Baojiashan also resides on the G30 motorway and connects Lianyungang (Northeast Chine) with Khorhas (border of Kazakhstan). (23)

In 2010, New York City turned on its TBM for the Second Avenue Subway line, a project 81 years in the making. The cutter head weighed 200-tons and commenced mining in May. The Second Ave TBM was manufactured 30 years prior by the Robbins company. The TBM was first used for MTA’s 63rd Street in the late 1970’s and was used on four other projects between the Second Ave Subway Line. It is common practice to refurbish and reuse TBM’s and excavation equipment because of durable and craftsmanship as well as the exceeding cost of expenditure.

In 2013, the massive 7000 tons and 57.5 feet wide TBM, began a tunnel to replace Seattle’s Alaskan Way Viaduct. Bertha, still stands today as the widest tunnel in North America and remains the largest TBM ever built. It was an epic undertaking to dig 1.7M (2.7KM) long underneath skyscrapers in the heart of the port city of Seattle to provide sufficient passageways to four lanes of motor traffic.
What Goes into a Tunnel?

There are many elements that make up a tunnel and its creation - from needs analysis and assessment to design to execution and maintenance, the process unfolds like a story. In this section, we will discuss all the tools and pieces that go into design, construction and long-term care of a tunnel.

To understand tunneling, there is some basic terminology associated with the field and work carried out. By definition, a tunnel is a long and narrow (length being at least twice as much as diameter) passageway underground, water or existing structures. Definition can also vary widely from source to source or by region. In the UK, a tunnel is defined as “a subsurface highway structure enclosed for a length of 150 meters (490ft) or more.” (9) In the USA, the National Fire Protections Association (NFPA) defines a tunnel as, “An underground structure with a design length greater than 23m (75ft) and a diameter greater than 1,800 millimeters or (5.9ft).” (10)

Other common terms include:

- Portal: the entrance or exit from ground surface to the tunnel.
- Trench: an excavation dug into the ground.
- Bore: the tube-like opening with a lining for ground support.
- Auger: circular drilling device used for horizontal digging.
- Liner: material that supports the ground and forms the bore interior
- Invert: the base interior level of the bore; “floor of tunnel” (11)
- Diameter: a straight line segment that passes through the center of the circle and whose endpoints lie on the circle (vertical length).
The purpose of a tunnel can vary greatly. A tunnel can be for traffic: foot, vehicular or rail. Tunnels are often used for utility purposes like water, sewage and hydroelectric power stations. Utility tunnels are also used for routing steam, cooled water, electrical power or telecom cable. Warfare, especially in the earlier 20th century, created a great need for secret tunnels in order to smuggle weapons, contraband and soldiers or people. There are even special tunnels for wildlife crossings to allow for various species to cross human-made barriers safely (environmental impact consideration).

The manufacturing process of tunneling and all of the necessary components and procedures is lengthy and has many seen and unseen facets. The overall encapsulation of tunneling as a whole can be organized by Preparation, Mining and Final Lining; all while involving Multidisciplinary and Cross-Collaboration Approaches, Quality Control and Waste/By-Product Management (example of Norway Lærdal Tunnel) to allow a tunnel to successfully come to completion. We will expound upon these terms throughout this section while the entire tunneling process from needs analysis to completion of the tunnel involves many branches of Civil-Engineering: Geotechnical, Environmental, Transportation, Urban, Materials, Construction, Hydraulics and Water, Structural, Geoinformatics as well Geosciences. Tunneling, in its entirety, also involves a variety of stakeholders and their input is essential for the success. The cross-collaboration of government agencies and officials, business and landowners, psychologists, emergency services (law, fire and medical) and engineers from all disciplines, miners and labor crews, safety and supervision personnel are just a few examples of the various team members working together at the different stages of tunneling from inception to closeout.

Preparation of a tunnel begins in land use management. Is there a need for a new tunnel or can roads, ferries or other forms of transit be used in its place? How does it benefit the community or end-users? Is it cost-effective? Economics of a tunnel are a major catalyst and guide to the creation of tunnels. Preliminary design of a tunnel also includes: geological survey, aerial photo interpretation, electrical resistivity tomography, seismic prospecting exploration and drilling survey for sampling soil.

A tunnel’s construction method is determined by many factors, including geology/ground conditions and environmental and community impact, as well as financial costs and resources required. During preliminary ground assessments, the construction method of a tunnel is also selected. Construction methods are as follows:

- Cut and Cover (bottom-up, top-down): used to build shallow tunnels. In this method, a trench is cut in the soil and it is covered by support that is capable of bearing the load that is upon it.
Within this method, the cutting can be done in two different ways. **Bottom-up** is when a tunnel is excavated under the surface using ground support. Top-down is when the support walls are constructed first by slurry walling or contiguous bored piling.

- **Bored Tunnel**: a modern technology in which tunnel boring machines (TBMs) are used to automate the work entirely and the cutting and routing of debris done continuously without stopping. TBMs are available in varying sizes (micro to large-diameter) and for different ground conditions. A TBM has a special pressurized compartment when working below the water table conditions. TBMs are very large and expensive to operate, and their transportation is the most difficult and costliest.

- **Hand-Digging (Hand-Mining)**: Often used at the start of tunnel process prior to other mechanized methods of tunneling. Hand-tunneling can be done by a physical labor force with tools like shovels. Hand-digging can also be automated by digging machines those mimic smaller amounts of quick excavation.

- **Clay Kicking**: used when soil conditions are strong clayey. An older method that is used for small works like sewage pipe installation. A hole is first dug into the ground once enough depth is reached a clay-kicker lies on a 45 degree angled plank in order to use the clay-kicker tool for excavation.

- **Shaft Method**: a tunnel is constructed at greater depth from the ground surface. The shaft is built up to the depth of where the tunnel is required. Shaft is a permanent structure, resembling a well with concrete walls. Shafts provide both inlet and outlet of tunnels. After the construction process, the shaft(s) can be used for ventilation or emergency exits.

- **Pipe Jacking**: used to construct tunnels under existing structures like road ways. In this method, specially made pipes are driven beneath ground using hydraulic jacks. The maximum size allowed is a 3.2 meter diameter for this type of tunneling.

- **Box Jacking**: Similar to Pipe Jacking, specially made boxes are driven into the soil. There is a cutting head at the front of the box and the excavated material is collected within the box. Some larger size tunnels can be excavated using box jacks up to 20 meters.
• Open Pit: also referred to as open cut or open-cast is a surface mining technique used for extracting rocks and minerals.

Sometimes techniques can be combined or used at different stages of mining. This can occur based on the difficulty of tunnels in uncertain or tougher terrain like underwater tunnels - which we’ll review in the Port of Miami example. The majority of tunnels have used a combined format for mining as follows:

“There are mainly three methods of excavation carried out, which is chosen based on the soil conditions. The first method is hand mining, which is the simplest method of all the methods available for excavation. This method makes use of picks, shovels or any pneumatic hand tools. This method proceeds with the help of a protective shield that provides face stability during excavation. The method is simple and is helpful when the site consists of varying soil conditions. This method is time-consuming.

“Another method is open face mechanical excavation, which is quite faster than the hand mining, as it uses mechanical devices. Here also, shields are provided, with power excavation devices. The shields provide access to the front face if any adjustments have to be made, which cannot be done manually under unexpected situations. The third method is Tunnel Boring Machine (TBM), which employs rotary cutter or disk cutters that are driven either hydraulically or electrically. The most improved version of TBM makes use of a pressure chamber. This method has high cost and has limited access. This method is restricted in circular tunnels.” (19)

Another common technique, often used in the beginning phases of mining, is the drill and blast method (typically done in conjunction to hand dug tunnels). Tunnel crews set explosives in place of the TBM and excavate after setting concrete culverts and rails. Micro tunneling is far less complicated and typically uses a laser for small diameter tunnels. Some common things micro tunneling is used for is storm drainage, sewer drains and utility casings.

“Drill and blast tunneling is a method of excavation involving the controlled use of explosives to break rock. It was the primary means of tunneling through rock prior to the advent of tunnel boring machines. Like trenchless construction and horizontal directional drilling, drill and blast tunneling is a form of subsurface construction. Large-diameter tunneling performed by drill-and-blast or tunnel boring machines is generally considered separate from trenchless technology.

“Drill and blast tunneling continues to be used despite the prevalence of tunnel boring machines. It may be more economical in shorter tunnels where the cost of a tunnel boring machine may be prohibitive. Significant advancements in blast technology, such as pumpable emulsion explosives, have also made it more attractive in some situations. The choice of tunneling method may vary from project to project.

This form of excavation became possible with the advent of gunpowder in the 1600’s, but it was not until the invention of dynamite in 1867 that the drill-and-blast method found greater success. Today an advanced form of explosive called ANFO (ammonium nitrate/fuel oil) provides more safety for workers.” (20)

Now we will take a look at the methods of tunneling with a shield without a TBM - this is where the shield is pushed forward by pressure and excavation takes place through windows that open up to
the back. This is far less complicated on the survey end because these are straight grade tunnels without any curves. As long as you have your shield properly placed, you use guide rails that are pushed through prior to tunneling.

“There are two major shield methods around: earth pressure balanced (EPB) and slurry type shield machine. Selection of the shield method depends on ground conditions, surface conditions, dimensions of the tunnel section, boring distance, tunnel alignment and construction period. Both are closed-face type shield machines, meaning the "head" part of the machine is "closed" and separated from the rear part of the machine. The "head" has a working chamber filled with soil or slurry between the cutting face and bulkhead to stabilize the cutting face under soil pressure. The EPB type shield machine turns the excavated soil into mud pressure and holds it under soil pressure to stabilize the cutting face. It has an excavation system to cut the soil, a mixing system to mix the excavated soil into mud pressure, a soil discharge system to discharge the soil and control system to keep the soil pressure uniform. Therefore, EPB may not be applicable for the rocky soil that is difficult to turn the excavated soil into slurry. It can be used at ground predominated by clayer soil. The slurry type shield machine, on the other hand, uses the external pressurized slurry to stabilize the cutting face, similar to bored piles or diaphragm walls using bentonite to contain the trench wall. The slurry is circulated to transport the excavated soil by fluid conveyance. Besides having an excavation system, the slurry type shield machine has slurry feed and discharge equipment to circulate and pressurize slurry and slurry processing equipment on the ground to adjust the slurry properties.” (21)

The entrance of a tunnel is made up of a retaining wall, which is typically built of metal sheet pilings and some form of concrete. Each tunnel has its own design, but the materials are typically metal and concrete because this makes for a durable tunnel entrance that will last for several decades. The entrance also usually contains entry rails and a jacking can for the launching of the TBM. The rails are usually set on concrete footers that are set to be durable enough to set the boring machine on. Both the steel rails and the jacking can are typically designed for removal after the TBM launches into the tunnel.

The entrance is also built for display: many roadway and subway tunnels will design the entrance so that the rings are not exposed, to look better for the public traveling through it. The entrance usually requires grading and finished surfacing after the tunnel is complete. For instance, roadway tunnels typically are filled with material and then concrete or asphalt is poured to allow smooth access into the tunnel. The entrance of the tunnel is typically the host of the first outer bracket that holds the total station and the back sight bracket. The first bracket is typically the only bracket that holds the robotic total station outside of the physical tunnel.

The next part we come in contact with is typically the inner lining of the tunnel. This is generally composed of steel rings or wooden boards that are interconnected with either large bolt patterns or metal connection joints. The tunnel rings are typically built to be durable and many times pre-cast concrete from a local plant that gets stored somewhere near the tunnel entrance.

The inner lining of the tunnel is usually an unfinished surface and built to construct the tunnel and support the weight above. Most tunnels will require additional surfacing inside the tunnel after completion. The finished surface in the tunnel differs from project to project. When micro tunneling, for example, the inner lining could be finished concrete or a pipe inserted for the flow of material. This is common for storm and sewer tunnels that require gravity to flow from one end to the other.
Finally, we need to consider how the tunnel will be illuminated.

“Good lighting should make driving through a tunnel like driving on the open road: it must allow drivers to enter, transit and exit the structure in safety and comfort. The standards for tunnel lighting vary from country to country, but they commonly state that the amount of light needed inside a tunnel depends on the level of light on the approach – which affects how easily drivers’ eyes can adapt to the change.

Generally, the lighting of a tunnel is divided into zones.

Access zone: First, the access zone, which is formed by the approach road itself, taking outside lighting into consideration. Drivers should be able to see clearly into the tunnel to detect any obstacles and react safely, instead of being confronted by a black hole.

Threshold zone: The first zone in the tunnel itself is the threshold zone, which extends for the same length as the stopping distance for the design speed of the road. The target luminance level for this zone (when using the L20 method) is derived from the portal luminance (L20) value factored for the class of tunnel. This level is maintained at 100 percent for the first half of the threshold zone, and can be reduced to 40 percent by the end of the zone.” (21)

Quality is thought through at a high level when during the inception of a tunnel project, even before the extensive planning stages embed it in the design as well as project rollout and eventual execution of planned work. Among the aims of Quality procedures the “risk assessment” has a significant role. As a guideline the following key steps should be taken to define the risk occurrence during planning and design:

• identify any hazards,
• assess risks (likelihood and consequences),
• use engineering and other means to eliminate risks (already included in the design),
• identify actions (countermeasures) to handle the unforeseen risks,
• assess any residual risks (the uncertainties which have not relevant consequences, including secondary risks)
• give approximate estimate of the costs and benefits of alternative risk mitigation options or strategies,
• allocate responsibilities for the unforeseen risks,
• select and implement any beneficial actions aimed to reduce the uncertainties.

Quality is also monitored and controlled with continued Surveying. Surveying is a critical quality control method when building a tunnel. Surveying allows the work executed to be measured against original plans and design and is both quality control and assurance. Quality assurance can be defined as "part of quality management focused on providing confidence that quality requirements will be fulfilled." Quality control can be defined as "part of quality management focused on fulfilling quality requirements." Quality requirements are a cross-collaboration effort amongst the sponsor, customer, performing as well as certifying and governing agencies.
Long-term care and maintenance is considered very early in the initiation of a tunnel project. Resources are secured during the planning phases of a project to ensure the tunnel can be sustained. Proper care for the tunnel’s lifespan is critical and is achieved through a variety of ways.

The American Association of State Highway and Transportation Officials; made up of agencies in states that have significant amounts of tunnels in their inventory includes: Chesapeake Bay Bridge and Tunnel (CBBT) District, the Port Authority of New York and New Jersey, and the Virginia DOT. In the West California DOT (Caltrans), the Colorado DOT, Massachusetts DOT (MassDOT), the Washington State DOT, the City of Seattle (DOT and Fire Department), and the Seattle Sound Transit System, Alaska DOT, the District of Columbia DOT, and the Pennsylvania DOT. The group has agreed upon a Current “Best Practices” for routine maintenance, repair and rehabilitation, which includes but is not limited to:

- Using MMIS that issues preventative maintenance work orders and tracks corrective work orders
- Holding an annual walk through with emergency personnel
- Installing a lane control signals systems in tunnels without lane control
- Monthly measurements of vibration in tunnels with ventilation equipment that is not fitted with real-time temperature and vibration monitoring systems
- Washing tunnels regularly
- Using hydro-demolition to remove deteriorated concrete
- Performing high-pressure cleaning of seep lines
- Checking emergency systems
- Phasing rehabilitation projects so that they are affordable considering other needs and upgrading life-safety systems during rehab
- Inspections at varying frequencies

**Tunnel Surveying and Deformation Monitoring**

Tunnel surveying typically falls under construction and is considered a sub-professional task; as such, you can perform it without a professional license. Nevertheless, this form of surveying is one of the most difficult tasks of the profession.

The navigation system is the surveyor’s main tool when surveying a tunnel. The navigation system is typically made up of a robotic total station, a back sight prism and a fore sight box that is mounted inside the tunnel. Common brands of automated total stations are Leica, Trimble and Topcon. The back sights are interchangeable, but it is important to use the set-up that comes with the total station. Many times the back sight prism is set at the same height above the tribrach for easy switching between stations. Most total stations are easily disconnected and interchangeable on top of the tribrach.

The navigation system often has an external battery with high capacity so it can run for a long time and you have fewer issues with the system being offline. If the system goes offline, it typically calls for a manual reset from the surveyor and TBM pilot. The onboard battery of the total station will start up if the external battery dies, but these have a much lower capacity and tend to drain rapidly.
The surveyor plays a crucial role along with the TBM pilot when determining the route of the boring machine, so the better the surveyor understands the navigation system and total station, the better for the project and tunnel construction company. Given all the workers on site that are held up, a shut down in tunnel production because of the navigation system being down can cause loss of several thousand dollars.

Typically, the difficulty of surveying the tunnel increases when the tunnel has a smaller diameter and/or more curves, and the longer it runs. Small diameter tunnels in particular are more difficult because you do not have as much room to set control points inside the tunnel and you are only able to survey with the line of sight method. When you increase the diameter of the tunnel, the surveyor is able to set points on the sidewalls and the resection method can be used.

The first step to successfully surveying a tunnel is to establish accurate ground control from one end of the tunnel to the other. This type of work often has to be performed under the supervision of a licensed professional land surveyor. Most companies will set control using a GPS system and run static sessions on the points.

“Static GPS surveying was the first method of GPS surveying used in the field, and it continues to be the primary technique for GPS/GNSS control today. Relative static positioning involves several stationary receivers’ simultaneously collecting data from at least four satellites during observation sessions that usually last from 30 minutes to 2 hours. A typical application of this method would be the determination of vectors, or baselines as they are called, between several static receivers to accuracies from 1 ppm to 0.1 ppm over tens of kilometers.” (13)

The GPS-surveyed points are typically traversed through using an accurate total station and often leveled through to ensure the horizontal and vertical accuracy meets the standard set for the construction of the tunnel. It is very important that all the site control is precise because the TBM needs accurate starting and ending coordinates to come out on target.

Line of sight surveying is when a single back sight is shot and then the total station rotates and shoots the fore sight. This is one of the least accurate forms of surveying because you only have one angle and distance to use for your calculation. It is also important and proper survey practice that your back sight is set at a longer distance than your fore sight. When you use the line of sight method, the back sight and occupied point are known coordinates and your fore sight is calculated from these.

It is important to have multiple control points set outside of the impact zone for tunneling. These points should be set in an array that allows for easy calculations and layout of the launching and receiving pits. The launching and receiving pits must accurately be set out because this is where your tunnel begins and ends. Points should be set far away from foot and vehicle traffic so they are not disturbed while work is being done on site.

The number of control points set should correspond with the difficulty and size of the tunnel and deformation monitoring plans. Certain large tunnels could have thousands of monitoring points that must be checked during different times of the TBM’s progression. Typically, standard monitoring points are just measured for elevation to see if the tunnel is causing ground issues at the surface. Anytime earth is moved or excavated, you risk the chance of cave-ins or ground swells. Monitoring points are
typically shot on a daily basis and dependent on tunnel chainage or stationing. When tunneling, the chainage or stationing is how far on the alignment you have progressed so far.

A lot of the layout for the rails and inside the tunnel are done by station offset which means physical points sit at a certain distance off the centerline either left or right and down or up. Left and down are typically reported as negative values. So for instance, if you have to measure 50 feet from the TBM, have a 30 foot long boring machine, and have tunneled 100 feet so far, you would have to measure all surface points between 20 feet and 150 feet of the tunnel entrance.

Surveying plays a major role in construction of the TBM. Most projects require you to measure the outer shield and make sure it is all at a certain distance off tunnel centerline. If the boring machine has an 8 foot outer diameter then each location of the shield should measure 4 feet from the centerline. If the shields had been previously used, you could run into small deviations even though the boring machine has been put exactly in the correct location of the rails.

“For a TBM tunnel project, it is essential to establish a flawless engineering survey system to ensure that the tunnel being excavated and built is in accordance with the predefined alignment. Most importantly, the ultimate goal is to construct the tunnel such that it does not exceed the allowable construction tolerance.

“A tunnel guidance system is tailor made for the TBM to continuously track the position and direction of the machine in course of excavating. The geo-spatial data of the machine is instantaneously displayed on the screen at the TBM control cabin. The pilot would make use of the information to steer the machine to match the design alignment.” (14)

The rails are also an important structure to lay out properly because your TBM typically rests on them at a certain angle. Many times the rails are designed at equal left and right offsets from the centerline and tilted from back to forward for proper launching of the shield and cutter head.

These monitoring points usually have a separate sheet in the construction plan set called instrumentation and monitoring. These plans guide you on which points need to be set as far as durability, stability and removability. Some more intricate tunnels require extensometers that actually extend down to the top of the tunnel. These are usually well protected and require additional care when setting.

When measuring these deformation points, surveyors typically use a digital level or a high accuracy total station for trigonometric leveling. Sometimes l-bar prisms must be used close to highways and railroad tracks to provide safety for the surveyors performing the measurements. These prisms allow a single surveyor to measure the points and cut down on project costs. The only issue with the l-bar prisms is that they are extremely expensive and sometimes can be damaged and cause false movement. This can also happen with traditional points, but is more noticeable since you have a physical person going and checking the point at each measurement.

“Monitoring of ground deformations in tunneling is a principal means for selecting the appropriate excavation and support methods among those foreseen in the design, for ensuring safety during tunnel construction (including personnel safety inside the tunnel and safety of structures located at ground surface) and, finally, for ensuring construction quality management according to ISO 9000. This briefly describes the types of ground deformation measurements often used in tunneling, the
difficulties in obtaining ground measurements and their subsequent evaluation, and the application of these measurements (a) in modeling tunnel excavation and support and (b) in establishing early warning systems against incipient ground collapses or damage to structures at ground surface.

Examples of ground deformation monitoring and their application in tunnel design and construction are illustrated via cases from the Jubilee Line Extension of the London Underground, from Lines 2 and 3 of the Athens Metro and from a nine-kilometer long mountain tunnel in Greece. In the first two examples, ground deformation monitoring aimed to ensure that structures at ground surface would not be harmed by the tunneling operations. In the third case, the objective was the optimization of the temporary support requirements as well as early warning against potential collapses.” (15)

The actual tunneling inside the tunnel or navigation tunneling can differ a great deal from job to job. A lot of factors such as tunnel size, navigation system programming, control quality and tunnel shape dictate which type of TBM is most effective to perform the task. Other factors can play a part in the selection of the TBM such as site access and what type of material you are planning to tunnel through. Some areas require different cutting teeth designed for hard rock.

The TBM typically has teeth on the cutting disk that remove the rock or dirt for tunnel production. With large boring machines, often the cutter head is surveyed prior to assembly to get an accurate portrayal of any imperfections or issues with spacing of the teeth. Cranes typically pick up the large cutter heads and surveyors direct them how to move it and set it properly.

Once inside the tunnel, typically automated total stations are used to track the progress of the boring machine. This gives an up to the second position check and allows the TBM pilot to make corrections based on survey measurements. The TBM pilot and surveyor work hand in hand to make sure the data is correct and the boring machine comes out on target.

“For every tunnel project, the navigation systems are individually adapted to the specific requirements. Alignment geometry, diameter, machine type and economic aspects are the key criteria for optimal selection. The different navigation systems are based either on tacheometry, laser or gyro technology.

When using a laser theodolite-target system, the photo-sensory target unit is mounted in the shield or on the machine frame of the TBM and its position is accurately determined upon installation. A laser theodolite that is fixed to the tunnel wall continuously controls the position of the target unit and determines the position to the tunnel axis during the entire tunneling process. The measurement direction is displayed and the horizontal and vertical deviation from the shield axis is derived by a visible laser beam. The hardware delivers reliable results and withstands strong vibrations, even in hard rock.” (16)

**Best Practices of Tunnel Surveying: Contracts, Plans and Processes**

Surveying is one of the most important tasks when building a tunnel. Without proper surveying techniques from start to finish, the successful completion of the tunnel is extremely unlikely. The first step to successfully surveying a tunnel is to be acquainted with the plan set and understand the design of the tunnel from the beginning (TBM Assembly) to the end (TBM Breakdown). Most plan sets are very
thorough and show designs down to the bolt patterns and monitoring specifics. It is important to look at the plan set while this is a conceptual idea from an aspect of feasibility as well. Sometimes you may catch a mistake or error on the plans that could cost the construction company a lot of money.

When creating a proposal for surveying a tunnel you must take into account travel time, materials and labor hours both in and out of the office. You also have to give yourself some time for research and to make sure you are qualified to be a part of the project. Most surveyors never get the chance to survey a tunnel in their career and do not understand the little nuances that must be figured out so a small mistake does not turn into something catastrophic, the worst case scenario being someone losing his or her life or the TBM going underground and never getting out.

Once you have a good understanding of the plans and feel confident in your ability to do the work, you then come up with a schedule. Schedules on tunnels vary from project to project. Some larger projects require a company to have a surveyor on site or on call 24 hours a day 7 days a week, and some adhere more closely to the 8 am-5 pm schedule that a construction company typically sticks too.

Another key factor to understanding the project is knowing the ins and outs of the TBM and navigation system. Each boring machine is unique in the set up and even though the surveyor does not build it, he will have to know how to properly measure it. When measuring the TBM, you must understand the specifications in which the project needs to be built. Tunnel surveying typically requires a much higher degree of accuracy than a survey of a road or standard topographical survey. This small window of error can make the difference in someone being hurt or the exit having to be completely redesigned after break through. There is a lot of effort going into what the finished product is supposed to look like, so if you come out 3 inches too low you will have to either compensate with concrete or recalculate the road exit.

Once you have a good handle on the plans, you should start writing out your scope of work for the tunnel. This will be the controlling document of what you are responsible for and should be well defined and scheduled. One good way to develop a scope is to look at similar projects; it is also beneficial to have someone else from your firm check your scope. If you have a Business Development Manager or Project Manager with available time, you should have them take a second look. In addition, you should check with whoever schedules the field work and make sure you will have adequate availability before submitting your bid or scope to the contracting company.

At this time, you may want to contact the contracting company with any questions or issues regarding scheduling and the plan set. This makes you look proactive, and could set you apart: a construction company involved in tunneling wants to hire a surveyor with an understanding of the process by which the tunnel will be constructed. Many tunnel construction companies will find a surveyor they are comfortable with and primarily use them when they are available even if they are not the cheapest option.

The next step is waiting to see if you are selected as the winning bidder. This process usually takes 2-3 days after the bids are submitted. If you get the project, now would be the time to go visit the project and see if there is anything else that was overlooked regarding the project. This is also the time when you can do your site planning and begin to look where you will set your primary control points.
Primary control points should be set near the tunnel entrance and exit far away from the impact zone and clear of trees and brush. Since these points will be shot in with GPS, you have to plan which time of the day would be the best to run static sessions on these points. These points should also be set with the intention that they will be around at minimum until the tunnel is completed, if not permanent. It is good practice to use a durable iron rod or iron pipe encased in concrete and a control box that is weatherproof. The minimum amount of points to set at the beginning and end would be two on each side. To be safe, most surveyors set at least one extra control point on each side of the tunnel.

After setting these points and running static sessions for two hours on them, the surveyor processes the data using OPUS and Trimble Business Center. These points form a control network in which your secondary points can be set. The next step is to traverse through these points, set secondary control points and run an adjustment to make sure your points fit well with the points on the other side of the tunnel.

“A traverse is a succession of straight lines along or through the area to be surveyed. The directions and lengths of these lines are determined by measurements taken in the field. A traverse is currently the most common of several possible methods for establishing a series or network of monuments with known positions on the ground. Such monuments are referred to as horizontal control points and collectively, they comprise the horizontal control for the project.

In the past, triangulation networks have served as horizontal control for larger areas, sometimes covering several states. They have been replaced recently in many places by GPS networks. GPS and other methods capitalizing on new technology may eventually replace traversing as a primary means of establishing horizontal control. Meanwhile, most surveys covering relatively small areas will continue to rely on traverses. Whatever method is employed to establish horizontal control, the result is to assign rectangular coordinates to each control point within the survey. This allows each point to be related to every other point with respect to distance and direction, as well as to permit areas to be calculated when needed.” (17)

You can calculate your closure using a data collector or post-processing software. The next step in the process is installing the monitoring points. As stated previously, these could be l-bar prisms, monuments encased in concrete or simple pk nails in railroad ties. Setting these points usually takes at least two surveyors because often they will be in traffic areas such as railroads or highways. Once these points are set, the next step is to run baseline values on them. Baselines are multiple measurements over the course of two or three days in which an average gives you your primary value for that point.

If a control point is destroyed, it is common practice to have to run new baseline values for that point. During the tunneling process, you will have a set amount of time to measure each of these monitoring points. The plan set should have threshold values set for these points and if your deviation runs larger than the threshold values, tunneling has to cease and the problem is assessed.

The next thing you have to do is any layout regarding the TBM like checking the cutter head and setting it. The launching pit is set out and gantry rails are built to specifics off the tunnel centerline. It is imperative that you have calculated the position of the tunnel alignment and have it keyed in your data collector. Once the rails are set, you level them to position with screws on concrete footers and the tunnel entrance is built usually of sheet piles driven down deep with Shotcrete.
All of this is typically constructed off offset points set by the surveyor. It is also good that the
surveyor is on site for real time checks of the rails and sheet piles. Setting the rails can take multiple
days alone depending on the size of the TBM. Once the rails are set, the surveyor typically marks the
tunnel centerline with a large target on the break in surface. The TBM is then assembled on the rails and
secondary checks are done on the shield.

"After a survey of a project has been completed and the stakes are set and marked, the required
amount of work needed to complete the job is determined by
using the information on these stakes. Since this information has to be used often during
construction and the original stakes can be destroyed or covered up
by carelessness or inexperienced operators, it is necessary to document this information. To
prevent the loss of reference information, you should transfer the required information from the stake
located in the immediate area of construction to a new stake. Set this stake far enough away so that it
will not be damaged or destroyed by equipment being operated in the construction area. This new stake
is called an offset stake and is identified by the symbol OF or an O." (18)

After the position of the boring machine is approved by the surveyor, the navigation system and
back sights are installed, as well as any secondary targets that the surveyor uses to calculate position of
the TBM. The boring machine is then set to launch once the navigation system is up and running, and
during this time the surveyor can layout the receiving pit, which is built much like the launching pit. The
main function of this receiving pit is for break through and possible turn around if you have two
neighboring tunnels running next to each other.

Now that everything is set outside the tunnel, the surveying inside the tunnel can begin. A
jacking can is used to project the cutter head into the break in wall with the robotic total station taking
readings on the box inside the cabin. As the TBM progresses, the navigation system updates and shows
real time progression of the boring machine.

When the boring machine outruns the back sight, meaning the fore sight shot on the box gets
longer than the measured back sight, a new bracket is set on the inside of the tunnel and you must set
coordinates on that and move your total station forward. In addition, secondary control can be set on
the tunnel sidewalls as you progress for checks on the position. The total station typically stays close on
line to the box on the TBM and the last back sight.
As the TBM progresses construction crews are building the tunnel while a conveyor belt removes the dirt out the back. Either concrete rings are set or wooden rails for the inside of the tunnel. Typically, the size of the tunnel and use dictates what type of material is being used. The crews also build rails inside the tunnel as the boring machine progresses that are used for transportation of carts within the tunnel. Not all tunnels are designed with inner rails.

The next step is the break through after the tunneling; here is where you determine how close the TBM came within target. The surveyor typically has a good idea because the guidance system is running the entire time. Sometimes the actual break through is a bit off where the guidance system predicts but is usually within a quarter of an inch horizontally and vertically if all steps were properly executed.

**Technology and Science of Tunnel Surveying and Deformation Monitoring**

In history as well as other sections of this work, we have explored - at length - the development and evolution of the technology utilized in tunneling. To meet all the engineering demands and expanding needs affecting populations, there has been constant innovation from previous methods and technologies. The question is where do we go in the future of tunneling?

GPS technology is now becoming available inside tunnels with repeaters. Waze is working on technology called “Waze Beacons” to keep drivers connected to GPS while driving through tunnels. Companies like FalTec are developing repeaters so that GPS equipment will soon be useable underground.

“If there is a clear view of the sky at ground level, a GPS antenna can be installed to receive data from the satellites. From here a coaxial cable is installed to carry the signal to the underground location
where it is required. If the cable run is too long, and losses become significant due to attenuation, line amplifiers are available to overcome this situation.

The example shown above illustrates an installation in the Crossrail tunnel underneath the streets of Central London. Large-bore mains water pipes are continuously monitored for leaks and the telemetry equipment requires accurate timing signals from a receiving antenna at street level.” (24)

Vicom has developed repeater systems designed for tunnels as well developing an artificial sky underground, which has become a cost effective way of using GPS in tunnels. “It consists of one Spectracom GPS time server with access to an outdoor GPS antenna and a network connection to GPS simulators. In addition to synchronizing the simulator’s date/time, the time server also acts as a RINEX server to provide the data about live constellation. Any number of GPS simulators are set to generate signals corresponding to a fixed known location so GPS devices continue to provide a position fix when cross live sky to GPS-denied boundaries.” (25)

uGPS Rapid Mapper is providing underground solutions as well, via new technology that obtains high-quality underground tunnel mapping using a decentralized sensor system. With this you can obtain 3D point clouds on a mobile platform. The datasets are robust and accurate and can be used to plan remediation or do as-builts of tunnels. This software enables you to get an accurate model of all the cracks and crevices that may cause issues with the tunnel over the course of time.

Their device operates from -30° to 60° Celsius and is built to seal moisture and dust, making it useful in even the most extreme tunneling conditions. This is a valuable tool for deformation monitoring inside the tunnel and shaft inspection.

GPS receivers are also being employed to do the deformation outside the tunnel, which was not thought feasible 10 years ago. With the new accuracy acquired by GPS, this data is deemed reliable to track movement on the surface.
Australians have started to use drones to map the insides of tunnels and mines as well.

“There are some environments (particularly underground), in which drones will receive no GPS signal and have to rely on other systems to guide themselves. Emesant’s system is called Hovermap. It gathers information through a device that is attached to the bottom of suitable industrial drones such as the Matrice 600. Alongside the normal video feed the drone captures through its camera, Emesant uses LIDAR (light detection and radar), collision avoidance sensors and GPS (when available) to create digital maps of underground environments.

This technology provides a real advantage to surveyors or site inspectors, who sometimes have to put their bodies on the line to assess the progress of a tunnel being drilled or whether a particular zone will be too risky to proceed with digging.

To date, Emesant has tested Hovermap devices to a depth of 2000 feet (600 meters) below ground in Western Australia. The underground drones fly through the tunnels and mines gathering data that is processed on a laptop.” (26)

This drone technology that has only been around a short time gives us a clear picture of what’s actually down below ground and allows us to gauge where the issues of the tunnels are located. It’s become a useful tool in developing very accurate 3D models using LIDAR technology.

Thermal vision cameras are also being attached to drones, creating new ways to monitor the tunnels within.

“Thermal vision cameras make pictures or video from heat, not visible light. Heat (infrared thermal radiation) and light are both parts of the electromagnetic spectrum. However, a camera, which can detect visible light will not see thermal radiation and vice versa.
Thermal cameras detect more than just heat. Heat vision cameras detect the tiny differences in heat, even as small as 0.01° Celsius. This information is then displayed as various colors on a display, in thermal software or apps.

“Everything in our lives give off thermal energy, even ice. The hotter something is, the more thermal energy it emits. This emitted thermal energy is called a “heat signature.”

The hotter the object, the more it radiates. The Sun obviously radiates off more energy than a hot cup of tea. The temperature also affects the wavelength and frequency of the radiated waves.

Objects at typical room temperatures radiate energy as infrared waves. When you see thermal photographs or videos of the radiation surrounding a person, animal or a hot mug of coffee, the energy radiated from the object is usually a range of wavelengths. This is usually referred to as an emission spectrum.

As the temperature of an object increases, the wavelengths within the spectra of the emitted radiation also decrease. Hotter objects emit shorter wavelength, higher frequency radiation.

For example, the coils of an electric toaster are considerably hotter than room temperature and emit electromagnetic radiation in the visible spectrum. The coils on the toaster glow red and we can feel the heat by putting our hands near the coils providing us with a convenient warning that the coils are hot.

Thermal radiation can occur through matter or through a region of space that is void of matter (a vacuum). The heat received on Earth from the Sun is the result of electromagnetic waves traveling through the void or vacuum of space between the Earth and the Sun.” (27)

Since 2017, drones and unmanned aerial vehicles (UAVs) have been used to help inspect subway tunnels in Singapore, so this technology is becoming widely used across the globe. The benefit of using drones to map the inside of tunnels is that it is very cost effective and can be done quickly causing
minimal stoppage of traffic. Also, fully autonomous drones are able to navigate through pitch-black caves.

The Army discussed mapping underground tunnels with ground robots as well. They are looking at it as a subterranean warfare technique that will be tested and used against the enemy. This could change the face of battle in the coming decades.

“In a Request for Information (RFI) published by the Army's Rapid Equipping Force (REF) on April 15 (2019), The Army challenged the defense industry to send in documentation for products at the model or prototype level of development within the next 30 days.”

The ideal tunnel mapping system will "be able to operate in GPS denied environment" and produce a 2D or 3D map, according to the RFI. It should be "rapidly deployable, easy and safe to operate, highly reliable and self-contained." It should be able to be mounted on an unmanned ground or aerial vehicle or be carried by soldiers.” (28)

It looks like GPS and drone technologies will be the main focus over the next several years with regards to surveying tunnels and underground spaces. As the technology and accuracy of the drone increases, the accuracy of the data achieved through mapping will correspond. We are just barely scratching the surface of this technology.

As-built mapping of tunnel rings and inner lining is becoming a more sophisticated process and evolving since tunneling has begun. In 2014-2015, the Port of Miami tunnel was mapped using a Leica Model TS-15 where it was set up at station points and set information on the tunnel size and diameter. The total station acted robotically and shot even spaced intervals. The one drawback to this process is the upper handle of the total station had to be removed for it to shoot straight up.

This was a very long process and each section mapped for deformation took a lot of time to get enough points to properly map the inside of the tunnel for problem areas. With scan stations becoming more popular, this task could have been completed much faster. From ground control, the scan station would have needed a few targets to pick up so that the data could be properly referenced in northing, easting and elevation.

Some of these scanners can cost upwards of 250k dollars, so it’s not feasible to buy one for a particular project. If the company had multiple projects to map this way, it would make a lot more sense to buy over rent. The processing software for these stations handle huge point clouds that take a lot of manual cleanup. It will also pick up things that you don’t want in your model and you will have to go through and manually remove them from the shot setups. In the early days of scanning, it could take 3 days of processing for every one day of measurement.

This software is extremely sophisticated and requires a great upfront cost to get started as well. Trimble, Leica and a few other companies are evolving the scanning process and clean up time with each new model that is released. This type of scanning is known as terrestrial laser scanning.

“In recent years, the use of terrestrial laser scanning (TLS) technique in engineering surveys is gaining an increasing interest due to the advantages of non-contact, rapidity, high accuracy, and large scale. Millions of accurate 3D points (mm level accuracy) can be delivered by this technique with a high point density in a short time (up to 1 million points per second), which makes it a potential technique for
large scale applications in engineering environments such as tunnels, bridges, and heritage buildings. Tunnels, in particular those with long lengths, create great challenges for surveyors to obtain the satisfactory scanned data.” (29)

The long length tunnels create issues because of data overlaps and clean up techniques, which can be very difficult to deal with. This machine typically shoots a 360-degree point cloud and many of the tunnel rings look very similar to the set prior or after. If surveying a short pedestrian tunnel or a water pipe, the process of clean-up is very less labor intensive to the data processing technician.

In 2017-2018, students from New Zealand and France were chosen to scan a newly opened tunnel that signified New Zealand’s efforts in World War 1. The LiDARRAS project signifies some of the huge advancements that tunnel scanning has made. This project in France was extremely significant because it preserved a piece of history and set a benchmark for terrestrial laser scanning. It was also selected in tunnel business magazine.

“Over the course of the project, the team completed nearly 1,000 scans using mainly the Trimble TX8 scanner, collecting about 100 gigapoints (100 billion points), making it one of the largest scanning projects of its kind processed in New Zealand. The final resampled point cloud at 2mm spacing is about 25 gigapoints. The control network was established for the tunnel and quarries but teams extended it to the outside so they could get good GNSS static positions and tie it to the regional grid.

In addition to the scans, 9,768 high-resolution photos were captured and processed into 814 panoramas. A georeferenced network of 32 control marks, including outside and underground marks, was surveyed with static GNSS and total stations. Closed traverses were used to carry control through the tunnels, and the network of observations was adjusted via least squares estimation. Scan data was processed in RealWorks to create a variety of digital data products, including raw scans; full scans that were registered, colored and georeferenced; a resampled point cloud at 2 mm between each point; and photo panoramas.” (30)
Author’s Experience in Tunnel Surveying and Deformation Monitoring

Port of Miami Tunnel – The Port of Miami Tunnel, also known as SR 887, is a 4,200 foot long tunnel that consists of two parallel tunnels. These tunnels are opposite in direction and terminate on Watson Island and Dodge Island. This project was done by Bouygues Construction and ran from May of 2010 to August of 2014. Robert Loane III worked on the first tunnel which ran from Watson Island to Dodge Island. The TBM was named Harriet and was built by Herrenknecht. Harriet was over 540 feet long, and had a radial cutting face over 40 feet in diameter. The TBM alone on this project cost over 45 million dollars.

Above is a photo of the two tunnels and the route under Biscayne Bay. The maximum height of the tunnel is at sea level and the minimum is -120 feet. This tunnel was built to alleviate the traffic going into and out of the Port. The tunnels focus was for the trucking industry, but it is open to the public to travel through.

The construction on Watson Island started with a huge launching pit that had to be drained by specialized divers due to the project being below sea level. Near the launching pit were hundreds of monitoring points that had to be measured on a set schedule based off where the boring machine was located at the time. The points were monitored using digital levels. The monitoring points on Dodge Island were installed l-bar prisms that were measured autonomously.

Two total stations were used inside the tunnel, one of them primarily hooked up to the guidance system at all times. Control points for the tunnel were set on brackets, which were screwed into the concrete. The control was hanging from the ceiling of the tunnel and on the sidewalls. Often resection methods were used in order to establish the most accurate line and distance for the tunnel navigation system running on the ceiling.

The TBM sat on rails to enter through the launching pit and landed on rails in the receiving pit. The tunnel was built six feet at a time with thick concrete rings that interlocked to each other in pre-
designed orders. Around 1,000 workers were on this project and it created around 700 jobs in the South Florida area. Divers would have to enter a hyperbaric chamber before entering the cutter head to change the teeth as the machine progressed through the tunnel.

The boring machine had a control room that could have doubled for something out of a science fiction movie. Real time calculations from the guidance system were constantly updating the position as the pilot decided where to push. The pilots were mainly from France and a lot of them had several years of experience and worked on large tunnels all over the world. Over the course of the tunnel, local pilots were trained on the TBM.

Robert was the lead surveyor inside the tunnel even though it was his first position out of college. He was chosen over surveyors with much more experience. The tunneling process was tough and sometimes Robert would get called at 3 A.M. to come to the site and level the machine. At times, the surveyors worked alternating 12 hour shifts so someone was always on site to make sure the tunneling never stopped.

The breakthrough ceremony was high profile with national news and high-ranking politicians from all over the United States on site to see Harriet break the shotcrete wall almost directly on target. Once the TBM surfaced on Dodge Island, it was disassembled and rebuilt on similar rails just north of the tunnel exit. The process then started again on the other side of the rails.

When tunneling under Biscayne Bay, specialized grout had to be injected into the sea floor to prevent the tunnel from flooding. During this period survey crews also set up automated monitoring at the Port of Miami with a Leica Total Station and l-bar prisms. The total station would run at designated times of an external battery that would require changing every couple days.

*The Michigan Ditch Tunnel* – The Michigan Ditch tunnel was a 766 foot long rib and board tunnel with a 98 inch outer diameter. This tunnel was designed for water to pass from one side of the ditch to another through an area that was basically impassible due to a mudslide. The water source was worth around 180 million dollars, so the tunnel was definitely a necessity.
This project was funded by the City of Fort Collins despite being located in Cameron Pass (Colorado). The design for this tunnel was finalized during the winter of 2015-2016 and construction would begin in June once enough snow melted to get the equipment and staff up a 2.5 mile narrow mountain road, which was only around 11 feet wide.

The narrow road was a determining factor on what equipment and size TBM would be able to accomplish this water tunnel, which would eventually hold a 5 feet diameter Hobias pipe. VMT (Navigation Systems) were onsite with surveyor Robert Loane III to begin the tunneling process, but before that, Robert had to set control and run levels from one side of the project to the other. Control for this project were steel bars with caps.

The TBM sat on rails and had an invisible axis on which it was designed to start and end. Robert was able to verify that the boring machine designed by Akkerman was set precisely on the rails by performing a resection and measuring the outer shields distance from the axis. The faces of the tunnel at the time of launch were sheet piles driven deep into the ground.

This project included a wide range of teamwork from BTC Construction, City of Fort Collins, Lithos Engineering, and Stantec along with the surveyors. The tunnel was mined from the downstream portal to the upstream portal. The design for this tunnel was two short tangents of less than 50 feet on each end with a 630 feet radius between them.

The radius was correlated with the deflection capabilities of the 5 feet diameter Hobias pipe, which sat inside the rib and board tunnel. Before the boring machine was launched, Robert affixed several targets in spots he would be able to shoot reflectorless with the Trimble S6 Total Station he used for the project. The navigation system used a separate Leica Total Station for the measurements to stay online. Robert was able to calculate the roll, pitch, yaw and location of the TBM through formulas he wrote in Microsoft Excel.

The Fossil Creek Pedestrian Tunnel – The Fossil Creek Pedestrian Tunnel was constructed under BNSF railroad in South Fort Collins, Colorado near the Redtail Grove Natural Areas. This tunnel was 70 feet long with a 170 inch diameter casing. The purpose of this was to connect two trail areas so the residents could travel from side to side of the railroad.
The first step for this tunnel was setting out stakes for the construction of the trails and the control, which were set outside of the tunneling area. Also at this time, the surveyors were building monument boxes, which were 3 feet long iron rods encased in steel with concrete foundation. These were set at a specific height so that settlement could accurately be recorded.

The challenge of this project was constructing a tunnel under an active rail line that had several trains move across it at different times of the day. Robert Loane III and crew had to set the points in a manner in which they were accessible quickly so they could be measured at multiple times during the day without train interference. Some of the monitoring points were required to be set directly in the track and had to be measured quickly with a flagger on site.

The retaining wall for the project was the next step before tunneling. This was set out simultaneously with the tunnel axis and the launching and receiving pits. This project was not tunneled using a TBM, but a shield in which dirt was extracted through flaps and the shield was pushed forward at a pace that allowed proper excavation without cave ins.

This project had significant movement in the railroad ballast due to tunneling and crews had to replenish the receding ballast so that the rails would not move. Movement in the rails would cause issues with the train traffic. During tunneling, the monitoring boxes and points set in the railroad ties were measured up to four times a day and required a crew onsite during all tunneling activities.

Robert created a spreadsheet that was editable in real time and the field crew was able to report any movement to BTC Construction, Lithos Engineering, Stantec and the City of Fort Collins when they requested updates. Every evening the day’s measurements would be sent out to a group of individuals and the deformation of the surface was monitored. Threshold values were set when the tunneling would have to cease to deal with any settlement issues.

**About the Author**

Robert T Loane III, is a Professional Land Surveyor currently located in the Denver, Colorado area. Robert has around twelve years of various experience in the Surveying and Mapping industry. He has worked on high profile construction projects across the United States from Florida to Alaska, most notably the Port of Miami Tunnel Project and the Urenco USA Uranium Enrichment Facility. Robert has been featured in both “The American Surveyor” and “POB” magazines for projects throughout the United States. He has completed his Bachelor’s of Science in Geomatics Engineering from Florida Atlantic University, Graduate Certificate in Geospatial Analysis from the University of Florida and will obtain his Master’s of Science from the University of Florida after the spring 2018 semester.
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