SELECTION CRITERIA FOR TUNNEL CONSTRUCTION

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Abstract:

Tunnels are necessary for mining, transportation and sanitary purposes allover the world. Construction of tunnels involves utilizing unique construction methods due to various characteristics like cost, constructability, resources and time. This paper covers different methods of tunnel construction by concentrating on different construction methods of every type of tunnels. Moreover, a comparative analysis is provided to show when to use every method of construction according to the conditions available. Two projects involving tunnels with different sizes and project conditions were studied and examined against the developed selection criteria in order to evaluate the validity of the applied construction methods in each case.

Keywords: Tunneling; Construction Engineering; Trenchless Technologies

1 INTRODUCTION.

Tunnels are underground passages or shafts that pass through a mountain or under a road or city or under water. Pedestrians and vehicles or trains can use such facilities. Some tunnels are used only for carrying water to other areas and some are used for cables in communication between cities. Also secret tunnels are built for military usage. The tunnels could be in rock layer, under sea or river and could be in soil filled with ground water. Each one of those cases has its own machines, safety precautions and type of labor. There are many shapes for tunnels; they are mainly circular tunnels, rectangular tunnels or Horseshoe (D-shaped) or oval (egg shaped). The main factors governing the shape choice are the construction method and soil condition, (FHWA, 2009). Until the early nineteenth century, tunnel construction in municipal areas was conceivable by applying one of two methods; either the cut-and-cover (trenched) excavation or by trenchless tunnel excavation using timber frames inside an advancing cavity and immediately lining with masonry. Those excavation methods were successfully applied in both cohesive and cohessionless soils, however they were limited to cases in which limited amount of water seepage occurs (Geodata S.p.A., 2008).
Bored tunnels are long tunnels that require selection of certain and specific excavation equipment to deal with different types of soil and rock. The process it usually performed using a tunnel boring machines

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(TBMs). These machines can be used for the boring in any material, from hard rock to sand, as well as conditions underneath the water table. Consequently, different types of TBMs exist. Hard rock TBMs can be open-shield or closed, depending on the rock support being installed in the tunnel. TBMs used in softer soils can be either an earth-pressure balance (EPB), a slurry shield (SS), or an open face TBM. Hence the main factor determining the type of TBM to be used in a project is the ground conditions (Mathy & Kahl, 2003) (Geodata S.p.A., 2008).

The first idea of tunneling under a water table was in reality suggested in 1806 by the Marc Isambard Brunel, for the realization of a tunnel under the river Neva in St. Petersburg. It was only in 1818 when he patented for the first time his invention: the shielded excavating machine. This first attempt of trenchless tunneling technology was applied first in 1825, in the excavation of the River Thames tunnel underpass. This first excavation attempt was done between 1825 and 1828 using a shield which was found unsuitable and so removed and substituted by a cast iron rectangular shield. Despite this accomplishment by Brunel, the dilemma of water control was not satisfactorily solved until the use of compressed air technology. The first successful applications of this face support technique were in Antwerp Dock tunnel, UK and in the Hudson river tunnel, New York (in 1879 and 1880 respectively). This significant advance made achievable to successfully drive 1130 m of tunnel and many other following tunnels. However, the associated worker health problems and method inefficiency (due to pressure non-uniformity) hindered the wide use of such methods until the innovative solution was found eight decades after which was based on using a highly dense medium to provide face support, initiating the development of the modern Slurry and earth pressure balance (EPB) machines (Geodata S.p.A., 2008).

On the other hand in unpopulated areas the usage of the drill-and-blast tunneling technique to construct tunnels through rocks was the most common practice since the invention of dynamite. Although this method is still used till today, the introduction of rock TBMs and their continuous advancements and the introduction and advancement of roadheader machinery has created other alternatives to the drill-and-blast technique (Girmscheid & Schexnayder, 2002) (Kwietnewski, Henn, & Brierly, 2011). However, the continuous advancements in the drill-and-blast techniques solve a lot of its occupational health and safety issues and keep it a good competitor to other methods (Girmscheid & Schexnayder, 2002) (Rafie, 2013).

While crossing waterways is usually done by TBMs boring the grounds beneath the waterways, in some cases it could be done using the immersed tunnel technique. Although it needs some conditions to be satisfied, this technique has been utilized for years and it has been increasingly proving itself as a sound technique in under-water tunnel construction in the past years (Lo & Tsang, 2008).

Another trenchless alternative that has been increasingly used is box jacking that involves utilizing hydraulic jacks to push prefabricated tunnel sections through the soils while performing simultaneous excavation within the jacked tunnel sections during jacking (Jacked Structures, 2011). Each of these tunneling techniques will be discussed within the next section of this paper and the selection criteria governing the choice of each of them will be developed in section 3.

2 CONSTRUCTION METHODS.

2.1 Trenched Methods

The trenched cut and cover tunnels are usually built through excavations and then covered in backfill material when it is done. It is usually used for tunnels that are needed in a shallow (within 10 to 12 m) place where excavation is easier and possible as it can be also economical. It is designed in a form of a rigid box and the quality and finishes is according to the area whether it is open urban areas or space limited areas. This tunneling method is economical, practical and easier in construction than most tunneling technologies. However, if the tunnel is underneath a city street it will cause traffic problems, dust and noise and if it is deeper than 12 meters it will not be economical any more. There are two types of construction methods, which are the bottom-up and top-down methods. The main difference is that the bottom-up technique is structurally independent of the support walls while the top-down technique is used when the side support walls are a main contributor in the tunnel structural system (FHWA, 2009).

In the bottom-up construction method the trench is excavated and then the tunneling takes place then the backfill is added. There are two methods to excavate the trench; using open cut or support system through excavation. This method is mainly used when there is no need for restoration for the ground surface, if there is enough space in the construction process, if it will not affect traffic and if there is no

need to emphasis on the sidewall deflection. While on using the top-down method, the tunnel walls must be added before the excavation process takes place, because it acts as a support. The roof is then constructed, after that the excavation starts; when the excavation is done the floor is constructed and connected to the wall. In some cases piles are added to support the walls. The conditions in which this method is used is when the risk of the wall falling is not in the direction of the road, if there is a high ground water table then it is difficult to construct the retaining walls for long tunnels (FHWA, 2009).
Within the bottom-up method the excavation should be easy without obstacles as it is shallow, the waterproof is easily applied on the inside and outside of the tunnel walls and the drainage systems are outside of the structure. All these merits makes it the most commonly used method of construction. However, this method needs a sound temporary support system for the structure, the dewatering may affect the infrastructure and it needs large space for construction. On the other hand, on using the top-down method the walls of the excavation are the tunnel's permanent walls not just temporarily, less need for large construction area, the roof is constructed easily as it is precast (in most of cases), the cost is lower and the duration is shorter than the bottom-up method. However, within this method no waterproofing for the outer side of the walls, the construction may be complicated as everything is connected, the excavation areas are limited and the connections between the walls and the slabs may not be as good as in the case of the bottom-up method and may cause leakage (FHWA, 2009).

2.2 Immersed Tunneling

Constructing a tunnel crossing a waterway is a task that could consume a lot of time and resources if done by boring or jacking technologies, a more feasible and efficient technique is to immerse the tunnel and let it rest on the seabed/riverbed. First, large marine excavators are used to excavate part of the riverbed/seabed to form the tunnel trench (and replace part of the soil if necessary). Second, the tunnel sections (steel or prefabricated concrete) are shipped from the construction basin. These sections should be designed to float on the water surface containing empty compartments that are then flooded by water to sink the section after reaching the required horizontal position. The section is hanged by four cables (mooring lines) to marine boats that would then lower the section into position. Once the section has been placed, stabilizing it starts by placing the foundations and the locking fill. When these are in position, the ballast exchange process can begin. When the element is first placed, negative buoyancy is provided by the internal or roof-based water tanks, external ballast boxes, or water cylinders. Another advancement in this field is the use of EPS (external positioning system) units that are clamped to the tunnel element and the lowering winches attached to lugs on the top of the EPS frame. When the tunnel element is immersed, the feet of the EPS land on the gravel bed at the same time as the tunnel element. Then the legs of the EPS frames are advanced to slightly lift the tunnel element and horizontal jacks are used to precisely position the element horizontally. This can be performed with an accuracy of 10 mm. Once the element is correctly positioned, the EPS units are then released from the tunnel element and lifted away by the lowering winches (Lunniss & Baber, 2013).
On deeper tunnels, it is preferable to minimize diver operations due to the greater risk at depth. In some cases diving bells are used, in other cases robotics could be used. Of course the application of such method is function of having good weather conditions, reasonable water currents and a riverbed/seabed of a sufficient bearing capacity. If one or more of these factors is absent it may force the use of other trenchless methods (Lo & Tsang, 2008).

2.3 Tunnel Boring

The tunnel boring process is usually done by using a tunnel boring machine (TBM). A typical TBM can excavate an average of 5-10 m/day depending on its size, type and site conditions. TBM's are divided according to the excavated soil into two main categories: Hard Rock, and Soft Ground TBM's. Hard rock TBM's are divided into two sub-categories: shielded and unshielded types. While soft ground TBM's are divided into four sub-categories: mechanically supported closed shield type, earth pressure balance (EPB) type, slurry shield (SS), and compressed air shield type (Geodata S.p.A., 2008). A TBM length ranges between 100-150 m depending on the manufacturer and its diameter. It is produced in different diameters with a minimum diameter of 1 m. The diameters of tunnels that a TBM could construct typically range from 2.5 m to 14 m (Girmscheid & Schexnayder, 2003).

The tunneling process starts by assembling the TBM in place, in order to do that a shaft must be excavated in the ground and the TBM is lowered in it. When the TBM starts excavation the precast concrete is placed to hold the soil up, it is done either automatically (the TBM pours it through arms) or manually where labor have to place the precast concrete segments. Another trench is excavated at the other end of the tunnel to lift the TBM up after finishing the tunnel excavation. The TBM then is lifted or disassembled after the excavation and the two shafts are closed. However, the process details change depending on the TBM type which is mainly a function of the soil type and project conditions. This method does not cause traffic disturbance, requires less labor and is safe in construction (if used properly). However, it is capital intensive, and as the TBM type varies with the soil condition, the TBM may not continue excavation if any surprises occur or if the soil properties change significantly and due to its shape and technique, the tunnels done by the TBM method could only be circular (Bilgin, Copur, & Balci, 2014).

2.3.1 Soft Ground Tunnel Boring

All soft ground TBM's are shielded as the soil may collapse as the machine proceeds boring. However, the shielding technique varies from one machine type to the other. When it comes to excavating soft grounds with TBM, the machine cutter head will require balancing pressure from the side of the machine, so the boring process is well-controlled. Concerning the earth pressure balance (EPB) type, it utilizes the excavated soil by mixing it with water, foaming agents and polymers to create muck in the working chamber behind the cutter head. The pressure of the muck is controlled by the pressure wall. A screw conveyor takes the mud out of the machine as the machine moves forward to carry out the extra mud from the working chamber. The rotational speed of the screw conveyor and the opening of its discharging gate are adjustable in order to control the pressure within the excavation chamber. The muck ejection rate and rotational speed of the screw conveyor must be equal to the machine excavation rate. This rate is controlled by thrust cylinders for appropriate face pressure control without dangerous stability problems. The amount of excavated material is controlled by either a weighing or a laser scanning system. These machines are usually used for excavation of fine sand, silt, and clay having low permeability. They are not very effective in soils having a percentage of fine material less than 10% and water heads over 4 bars (Bilgin, Copur, & Balci, 2014).

The slurry shield (SS) TBM works with the same concept of the EPB type however, the cutter head is balanced by bentonite slurry. Moreover, the screw conveyor is replaced by two pipes that are the slurry feed and return to pump the slurry in and out of the working chamber. The slurry system works in a closed circuit as the slurry is reused after reprocessing. On the other hand, in stable ground and rock conditions, SS TBMs can be used in open mode without giving any face pressure (provided the cutters are changed). They are normally used to excavate gravel, coarse-medium sized sands, and silty and/or clayey sands of a hydraulic permeability between 10^{-8} and 10^{-2} m/s (Bilgin, Copur, & Balci, 2014).

In compressed air TBMs, the rotating cutter-heads are the means of excavation whereas face support is ensured by compressed air at an adequate level to balance the hydrostatic pressure of the ground water. The excavated soil is extracted from the pressurized excavation chamber using a rotary hopper and then conveyed to the main mucking system (Geodata S.p.A., 2008). These machines are normally used in soils having permeability lower than 10^{-4} m/s as any increase in soil permeability above this value would cause the air to escape. The air pressure in the cutter-head chamber should be only be set to be equal to the water pressure in the invert of tunnel, earth pressure has to be balanced additionally by natural or mechanical support. Hence, if underground water is absent, the system can be used in an opened mode (without face pressure). The air pressure is typically limited to a maximum pressure of 4 bar (3 bar above the atmospheric pressure) due to the danger of Caisson's disease, this increases work time due to compression and decompression of staff, and increases the risk of fire and smoke. This technology also requires a huge compressed air generation system on the surface. Due to all of these reasons, the use of compressed air shields is decreasing (Bilgin, Copur, & Balci, 2014).

On the other hand, mechanically supported, open face shielded TBMs, equipped with full round protective shields immediately behind the tunnel face could be used in some special cases. The cutter-head performs its role as a cutter-head and also performs another role of supporting the tunnel face through using movable plates and thrust against the face via special hydraulic jacks. The fragments are extracted through adjustable openings or buckets and transferred to the primary mucking system. This method

could be used to excavate tunnels through self-supporting ground as weak rock and fully or partially cohesive soils in which groundwater is minimal (Geodata S.p.A., 2008).
The concept of designing convertible multi-mode machines was first initiated in the early 1980s setting the starting point leading to the development of what is now called the “Mixshield”. The basic concept is to have a machine that is mechanically capable of switching between the two of the main three modes of EPB, SS and open single shield TBM’s. The past three decades experienced developments of machines that could change their mode of operation between open face single shield and closed EPB shield, and other machines that could change their mode of operation between closed slurry shield and open face single shield and a third family of machines that could change their mode of operation between EPB and SS modes. These developments were mainly done through altering the mechanical components of the machines and/or combining components of two types within the same machine. Such costly developments broaden the type of soil that could be bored within a single project reducing the risks of stopping the excavation due to soil type change (Burger, 2014) (Kondo, Iihara, & Kishimoto, 2006).

2.3.2 Hard Rock Tunnel Boring

TBMs are appropriate for cutting hard rock of compressive strength ranging between 50–300 MPa. However, and as abrasiveness relates to the intensity of wear sustained by the cutting tools, the rock should not be too highly abrasive. Minerals, having a high degree of hardness like quartz are highly abrasive. Hence, rock formations of compressive strengths exceeding 300 MPa, high toughness or high tensile strength, or having a high proportion of minerals with an abrasive effect represent the economic limits for using such machines (Girmscheid & Schexnayder, 2003).
The unshielded open type (also called “gripper” or “main beam”) TBM has no cover on its components as it depends on the arching effect created in the excavated rock. The cutter-head of the TBM has disks and is pushed against the excavated tunnel with hydraulic thrust cylinders. A system of grippers pushes on the sidewalls of the tunnel locking the TBM in place while the thrust cylinders extend, allowing the cutter-head to go forward. After completing a boring stroke, the boring process is paused and the machine is moved ahead, with the TBM being stabilized by an additional support system. The conveyor belt transfers the muck along the TBM length till reaching the backup area. The arching effect in most soils cannot be ensured permanently without reinforcement, so as the machine bores, fixing rings of reinforced concrete along the tunnel starts in order to create the new tunnel body. Each ring is divided to a number of shells. The shells are pre-cast and ready to be fixed together and to the soil with bolts (Bilgin, Copur, & Balci, 2014). For this type of machines, the rock compressive strength should be between 100 and 300 MPa. A rock formation of a compressive strength less than 100 MPa can limit the holding capacity of the grippers and reduce the maximum axial thrusting force of the TBM (Girmscheid & Schexnayder, 2003).
The single-shielded type TBM is also a hard rock type machine. It applies nearly the same cutting technique as the opened type however the TBM is shielded, so that the bored rock does not collapse on the machine. The shielded TBM has arms that fix the rings to the rock as it moves. Therefore as the TBM moves forward it fixes directly the ring segments without an aid of an external crew, but the crew on the machine itself. Another type of shielded TBM’s has a double-shield as the telescopic shield extends on advancing the machine hence shielding the TBM from the surrounding ground while the gripper shield remains motionless during boring (Bilgin, Copur, & Balci, 2014). This type of TBM’s is longer in length and less susceptible to rock collapses. The merit of the shielded TBMs is that even if the rock has a relatively low compressive strength of approximately 50 MPa and a low rock-splitting strength of 5 MPa, the shielded TBM can do the job with minimal risks. In the case of grounds having a tendency to collapse, shielded TBMs characterize a suitable operational solution (Girmscheid & Schexnayder, 2003).

2.4 Jacked Box Tunneling

Within this trenchless method of construction, tunnel sections are prefabricated and then are pushed one after the other by hydraulic jacks. In this method, the tunnel concrete section is completely constructed on one end of the tunnel and placed in the jacking pit that is excavated at one end of the tunnel. Then, excavation equipment is used to excavate the soil in front of the tunnel section. However, as the clear height of the tunnel is high, temporary slab is constructed in between for excavating equipments to be able to completely dig soil in front of the tunnel section. After the loose soil is transported out of the

section, hydraulic jacks are used to push the tunnel forward. The same procedures before are done continuously until the tunnel is in its final position (Jacked Structures, 2011).
Within this method, the jacked tunnel could progress at a rate between 1 – 2 m/day, the maximum rate recorded ever was 4 m/day. Taking into consideration the need for mobilization time to construct and prepare the jacking pit which is comparable with the mobilization time in the tunnel boring methods and the advancement rate that is lower than that of most of TBM's, this method is not a competitor to TBM's in long tunnels. However, its merits over TBM's is the significantly lower levels of vibration and disturbance to the surrounding soils and structures. Hence, it is most commonly used to cross tunnels beneath railways, underground structures and underground tunnels as it nearly guarantees that these important facilities will not be affected by high levels of vibrations (Kruger & Pty, 2013).

2.5 Drill-and-Blast Method

This tunneling method involves the use of explosives. Drilling rigs are used to bore blast holes on the proposed tunnel surface to a designated depth for blasting. In the drill-and-blast method, a drilling jumbo is used to drill a predetermined pattern of holes to a selected depth in the rock face of the proposed tunnel's path. The drilled holes are then filled with explosives such as dynamite. The charges are then detonated, causing the rock break. The loosened debris or muck is then dislodged and hauled away. Other tools such as a pneumatic drill or hand tools are then used in smoothing out the surface of the blasted rock. The most important principle associated with the drill-and-blast method is that the energy generated from the explosives must be allowed to be directed in the correct alignment. To carry this out properly, the geological condition of the rock bed, the angle, size, and spacing of the drill holes, and the energy factor have to be taken into consideration and precisely calculated (FHWA, 2009).
The advancement of long tunnels through hard rocks before inventing TBMs relied on the drill-and-blast method. Today, the drill-and-blast method is still widely used in building shorter tunnels through hard rock where the use of tunnel boring machines is not justified and too expensive. In smaller tunnels, drills are individually mounted on bars or columns with an adjustable clamp that permits movement. In a larger tunnel, drills are mounted onto a drilling jumbo, a type of portable carriage with one or multiple platforms that are outfitted with bars, columns, and/or booms to support simultaneous drilling in any number of patterns. The jumbo moves through the tunnel as excavation proceeds. The environmental impacts in terms of noise and dust are high however localized in the area near the tunnel portal. This method is much faster than excavating rocks using the cut and cover method however on comparing it to hard rock TBM's it takes less time in terms of mobilization which makes it much faster and cost effective to drill-and-blast short tunnels and use the TBM's in longer ones as the TBM excavation cycle takes less time. In addition to that, blasting would significantly reduce the duration of vibration, though the vibration level would be higher compared with bored tunneling (Rafie, 2013) (Girmscheid & Schexnayder, 2002).

2.6 Sequential Excavation Method (SEM)

This method is also referred to as the New Austrian Tunneling Method (NATM) as it was first initiated in Austria in the early 1960's. The concept is based on utilizing the self-supporting capability of the ground hence achieving an economically sound ground support. Hence, it is mainly used with dry soil where road headers and/or backhoes are used for the excavation. A typical cross section for a tunnel constructed using this method involves usually an ovoid shape to endorse smooth stress distribution in the ground around the new opening. By adjusting the construction sequence represented mainly in round length, support installation timing and support type, this method could be used for rock and cohesive soils. The major difference in using this method in rock tunneling than soft ground tunneling is the properties of the liner and its connection to the soil on which it is attached. Within this method, the most commonly used support element is shotcreting because it's capable of providing interlocking and continuous support to the ground. The SEM has a dual lining technique in which a waterproof membrane (mostly PVC) is inserted in between the shotcrete layer (100-400 mm thick) and another final layer of cast in place concrete lining (about 300 mm thick). SEM is generally slower than TBM's when it comes to constructing long tunnels as the production (advancement) rate of a TBM is typically faster than the SEM. However, as the mobilization time of a TBM is much longer than that of the SEM, the SEM is more suitable for construction of short tunnels, large openings such as stations, special cases involving unusual or complex shapes such as intersections and enlargements (FHWA, 2009).

3 CONSTRUCTION METHODS SELECTION CRITERIA.

Based on the discussion of the different methods presented in the previous section, a selection criteria could be developed to aid the decision making process concerning the tunnel construction methods. Typically, the trenched method is more economical than trenchless methods however, if the tunnel is planned to be underneath a city street or crossing water ways or if it is deeper than 12 meters it will not be economical to use the trenched method. The soil type, tunnel dimensions and location are the most important factors governing the choice between the different trenchless methods. The time frame, resources (especially equipment), cost, level of risk and constructability also affect the method selection. On the other hand, on using TBM's the main factors governing the choice between different TBM's is the soil type, conditions and the ground water table. Each TBM type could only bore in certain type(s) of soil which could be problematic in case of considerable soil type change along the tunnel length. However, the advancements achieved in designing and using multi-mode TBM's solved a great portion of this problem but this is on the account of the higher level of mechanization reflected in an increase in the price of the TBM itself. A summary of the selection criteria between different TBM's could be found in Table 1.

Table 1: Selection criteria for TBM's.

Ground type	TBM type	Suitable Ground Condition	Cost	Speed	Risks
Soft Ground	EPB	Water head< 4 bars & fine materials> 10%	High	Moderate	Low
	SS	Permeability from 10^{-8} to 10^{-2} m/s	High	Moderate	Low
	Open face	weak rock, fully/partially cohesive soils with low GWT	Moderate	High	Moderate
Multi-mode TBM's		Most of soil types	Highest	Variable	Low
Hard Rock	Unshielded	Rock compressive strength from 100 to 300 MPa	Moderate	Highest	Highest
	Single-shield	Rock compressive strength from 50 to 300 MPa	High	Moderate	Moderate
	Double-shield		Highest	Moderate	Lowest

The high level of vibrations caused by a TBM during boring could negatively affect neighboring structures or facilities (especially if underground), in such cases the use of the jacked box tunneling technique is more appropriate as its effect on neighboring structures is minimal although its productivity is less than that of TBM's while its mobilization time is shorter than that of TBM's, that makes it more suitable in shorter tunneling projects. On rock tunneling, and similar to the jacked box method, when comparing the drill-and-blast method to hard rock TBM's it takes less time in terms of mobilization while the method productivity is lower making it much faster and cost effective to drill-and-blast short tunnels and use the TBM's in longer ones. Typically, the drill-and-blast method is the least safe however with modern advancements in the mechanization of the process and the use of robotics this issue could be solved. Again the same productivity issue comes into the picture when comparing the SEM to TBM's as SEM is generally slower than TBM's when it comes to constructing long tunnels as the production (advancement) rate of a TBM is typically faster than the SEM while the SEM takes less time in terms of mobilization. Hence, the SEM is more suitable for construction of short tunnels, large openings such as stations, special cases involving unusual or complex shapes such as intersections and enlargements. Also, and as this method principally depends on the soil arching effect to carry istelf, special attention should be taken on using it in areas with high seismic activity or ground water table or vibrational loads.

Due to its own nature, the immersed tunneling method is only used in cases of water crossings and as it mainly depends on floating the tunnel sections in water and resting it on the seabed/riverbed (replacing the first 1-2 m is a common practice), the method is highly dependent on the weather conditions, water currents and the bearing capacity of the soil(s) on which the tunnel sections will rest. If the proper conditions are present, this method is more efficient than other trenchless methods as the fastest of all trenchless methods. A summary of the selection criteria for trenchless methods is presented in Table 2.

Table 2: Selection criteria for trenchless tunnel construction methods.

	TBM	Jacked Box	Drill-and-blast	SEM	Immersed
Suitable Soil Type	Various Soils	Soft grounds	Rocks	Rock and cohesive soils	Requires high bearing capacity
Cost	Cost saving for long tunnels	Cost saving for short tunnels			Cost efficient
Level of Mechanization	Highly mechanized	Highly mechanized	Moderately mechanized		Highly mechanized
Constructability	Soil dependent	Moderate	Depends on project conditions		
Productivity	High	Low	Moderate	Moderate	Highest
Mobilization Time	Long	Moderate	Short	Short	Moderate
Construction Risk	Soil dependent	Soil dependent	Highest	Project dependent	Weather dependent
Safety	Depends on machine type	Safe	Least safe	Project dependent	Weather dependent
Most Suitable Location	Long Tunnels	Short tunnels beneath/beside structures	Short in-the-rock tunnels	Short tunnels, large openings, complex shapes	Water crossings

4 CASE STUDIES.

4.1 The Boston Big Dig, Boston, USA

The aim of this megaproject was to reroute the central downtown highway Central Artery (Interstate 93) into a 5.6-km tunnel. The project also included the construction of the Ted Williams Tunnel (extending Interstate 90 to Logan International Airport), the Leonard P. Zakim Bunker Hill Memorial Bridge over the Charles River, and the Rose Kennedy Greenway in the space vacated by the previous I-93 elevated roadway. This project is the most expensive highway constructed in the United States with a cost of $14.6 billion dollars and was completed after 20 years of construction (MassDOT, 2014).

4.1.1 Applied Method

The Ted Williams Tunnel consisted of two main sections: the coast section and the under-water section. The coastal section was constructed with a bottom-up open cut trench tunneling technique. The under-water part contained two main sections: steel sections shipped from Baltimore on the east coast and cast-in-place concrete sections on the west coast. The under-water section was constructed using the immersed tunneling method as large marine excavators excavated a part of the Charles river bed to form the tunnel trench. Second, similar to the east coast section, the underwater sections were steel and were shipped from Baltimore. These sections were designed to float on the water surface and contained empty compartments that were then flooded by water to sink the section after reaching the position of the section floating. The section was hanged by four cables to a marine boat that would then lower the section into position exactly. After connecting the sections the water was sucked out (MassDOT, 2014).
The construction of this I-90 highway included constructing two tunnels with different construction methods. The Fort Point Tunnel was one of the most challenging parts in the project as it was positioned few meters above a metro line. In order to rest this immersed tunnel on the riverbed, the tunnel load had to be transferred to a strong soil layer without affecting the metro line. As a result, piles were driven at the two sides of the metro to load the tunnel on the lower bed rocks instead of loading the tunnel on the soil above the metro. Moreover, this tunnel was constructed to cross the Fort Point channel, which is very small in terms of width causing limited space for construction. As a result, the builders took advantage of an empty space on one side of the channel to be the construction site of the tunnel. Then floating, sinking and connecting of the three immersed tunnel section was performed in a manner similar to that applied in constructing the under-water Ted Williams section. The second (smaller) section of this tunnel passes

under the railway network of the city. As a result, the tunneling should cause minimal disturbances under the rail to avoid derailment of the trains. The main problem was that Boston is mainly constructed over landfill composed of blue clay. To solve this problem, ground freezing was applied to solidify the soil and make it hold itself during the digging process. Moreover, the box jacking method of construction was used to ensure the trains safety. In this method, the tunnel concrete section was completely constructed on one end of the tunnel. Then, equipments were used to excavate the soil in front of the tunnel section. However, as the clear height of the tunnel was high, a temporary slab was constructed in between for excavating equipments to be able to completely dig soil in front of the tunnel section. After the loose soil was transported out of the section, hydraulic jacks were used to push the tunnel forward. The same procedures were done continuously until the tunnel was in its final position (MassDOT, 2014).

4.1.2 Construction Method Evaluation

The decision of using a cut-and-cover decision in the first section was appropriate and the most economic choice as using a trenchless technique in a location in which the trenched method could be used would have been a waste of money. The two under-water sections had a situation in which the usage of the immersed tunneling technique was the optimum solution as the weather and water currents were suitable for the pre-dredging, floating and sinking operations to take safely place and the soil layer beneath was capable of bearing the tunnel load, so using TBM's in such case would have been a waste of time and money. Finally the section that was tunneled using the box jacking technique had to be done using that method as using a TBM would have induced vibrations that could have harmed the railway above.

4.2 The Channel Tunnel, France – UK

The channel tunnel also known as the Chunnel, is a tunnel built between Britain and France across the English Channel to connect the two countries, and furthermore connect Britain to the rest of Europe. The channel tunnel, to this day is the tunnel with the longest underwater section in the world of 37.9 km and was twice as long as any previous tunnel underwater, with its lowest point at 75m deep. It consists of two main rail tunnels and one-service tunnels, with 245 cross passages across its route from the main tunnels to the service/escape tunnels. The digging was done by TBM's at both ends (British and French) and met in the mid-point of the channel to complete the entire length (National Geographic, 2004).

4.2.1 Applied Method

Before construction, twelve boreholes were drilled across the channel. The layer of rock that was being investigated was blue chalk as this layer is impervious providing protection from water, which could flood the tunnel or make it collapse. Consequently the course for the tunnel route was established and excavation of drilled shafts at took place at both ends. Five TBM's were used in the project each designed for the geology of a specific length of the project. The French side was expecting to encounter fractured rock, which would allow water through causing flooding, and therefore EPBM's were used to withstand high water pressures while boring. The British team was provided with two double shielded TBM's as less water inflows were predicted. The longest TBM in this project was 200 m long. The TBM's were lowered into the drilled shafts at both ends then the TBM boring started. While the machine rotates under the sea, the spoil of the tunnel is taken from the back as it digs, and the earth is loaded into railway wagons and carried to the surface for disposal. As it rotates, prefabricated concrete tunnel sections (transported to the front of the tunnel using temporary railways) are placed continuously using hydraulic arms to make a support around which as acts as a permanent lining. The installed segments are then connected to the previously installed ones and grouted together to form the tunnel lining. After the installation of the slab segment the TBM uses it as a stationary unit for its advancement. A laser guide was used to direct the TBM excavation, to make sure it's on course, however, because it's underground, they looked back to show where they should have been, rather than forward to where they should go. Laser beams hits back to the tunnels starting point to compare it with the TBM location. Computers then check this data with the surveyor's course coordinates. This process was continued until both TBMs reach each other and the last segment was demolished with a jackhammer to connect the two tunnels. Ventilation in the tunnel was important to keep the air fresh. A huge ventilation system was installed at the tunnel face to achieve adequate ventilation throughout the tunnel. When water logged earth was encountered steel sections were installed to stop the leakage and flooding of the tunnel. Finally, the British TBM dove beneath the

French side of the tunnel and was disposed in this fashion while the French TBM it was pulled out of the British side of the channel and disposed of on the surface (National Geographic, 2004).

4.2.2 Construction Method Evaluation

The channel between the UK and France is well known for unstable weather conditions and extreme currents. Hence, using the immersed tunneling technique would have been difficult and of very high risks. On the other hand, the box jacking method was unsuitable for usage in case of such a long tunnel. Hence, using TBM's in such case was the only possible option. However, the type of TBM's could have been altered to use multi-mode TBM's to take into account the possible variation in ground conditions.

5 CONCLUSIONS AND RECOMMENDATIONS.

When examining the methods applied in the two cases discussed in section 4 of this paper against the selection criteria developed in section 3, the selection criteria proved that it covered the different aspects governing the selection of the most suitable methods for different tunnel construction cases. The most governing factor of choice is the soil conditions and following that comes the safety, level of risk, constructability, speed and cost. Hence, it is highly recommended when using the selection criteria matrix to take all the factors governing the method selection into account as neglecting some of them could cause serious problems that are difficult in fixing.

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