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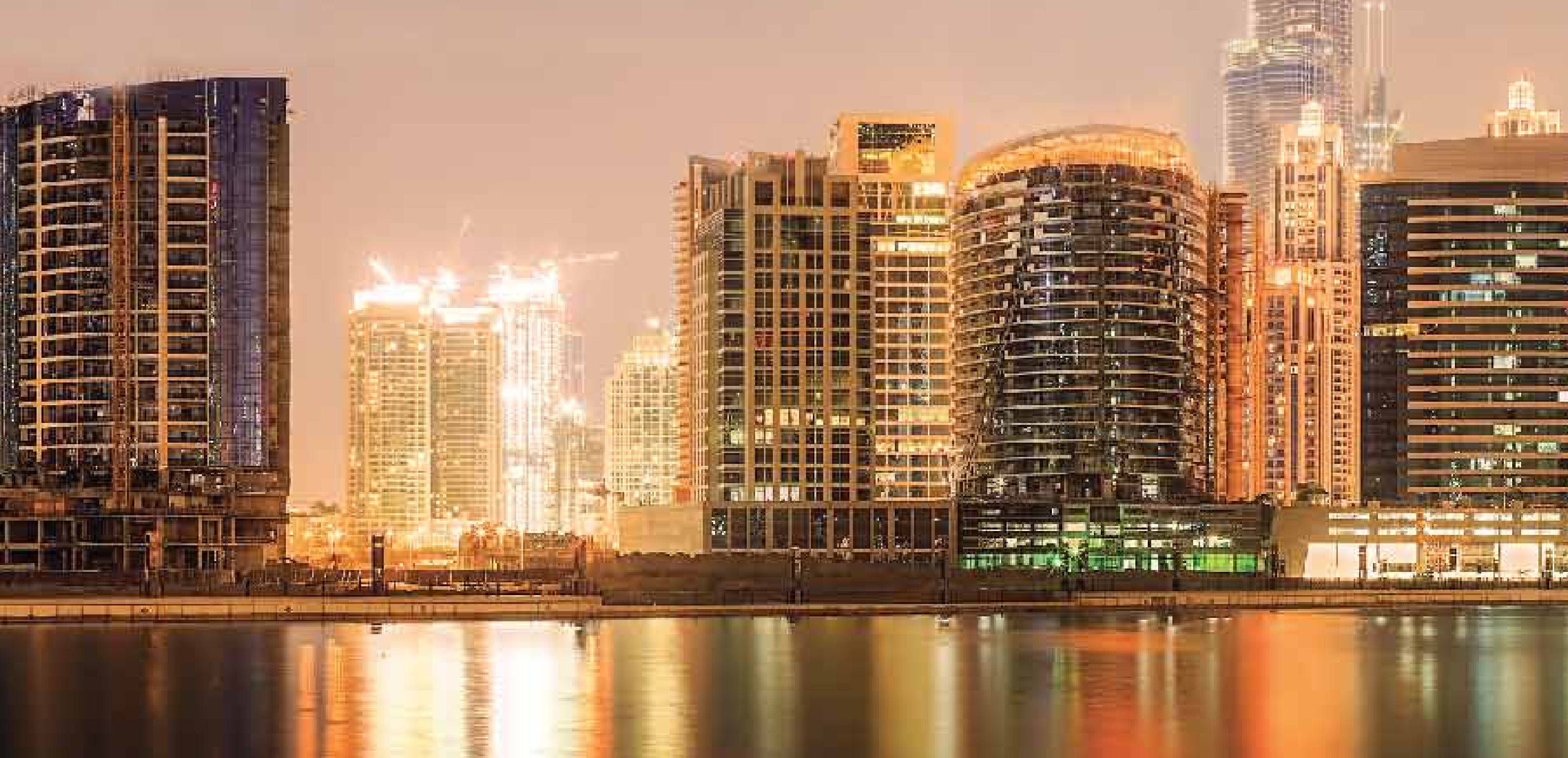

Extruded Concrete Lining

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ABSTRACT

The most commonly used methods for tunnel construction are the NATM (New Austrian Tunneling Method) and the TBMs (Tunnel Boring Machines). These techniques typically use sprayed concrete and precast segments, respectively.

Extruded Concrete Lining (ECL) has recently been used as an innovative alternative to tunnel lining. This technique was developed in the last century by European and Japanese entities. Its use was in transportation tunnels, energy and sanitation. Two methodologies for the execution of this lining will be demonstrated. The first is an initiative of BraBo (Brazilian Borer), still in a conceptual character. It was proposed to use a sliding shape and differentiated rheologies for the cementitious paste. Another alternative was the description of the SENS (Shield Extruded NATM System), which was used in the Sanbongi Hara tunnel in Japan. In this case, a collapsible form was realized to aid in the concreting activity.

Studies have been compiled that show some improvements when compared to current solutions during construction and operation. The advantages of production, logistic, watertightness, lower bending moment, construction performance and costs are discussed. For this, a comparison will be made between the different excavation methods, in terms of both the performance of the lining and the logistics (transport and storage) and the executive process.

A table was presented compiling the characteristics of three types of execution: the NATM with use of projected concrete, the TBM with use of concrete segments and the TBM with the use of extruded concrete. Some advantages may be realized when the extrusion is chosen as the lining and support material of a tunnel.

Key Words: tunnel lining; extruded concrete; ECL; SENS; TBM.

1. INTRODUCTION

The use of tunnels is perceived since the beginnings of nature. The environment itself unconsciously creates tunnels of water and larva, in a natural sense of finding the slightest effort to cross an obstacle. Nevertheless, some animals like ants, termites and even rodents, use tunnels for transport and shelter.

Tunneling techniques have evolved over the years, but it is still difficult to maintain standardization of excavation methods. This is because each tunnel is unique because of its constructive characteristics and the soil / rocky mass that surrounds it. Out of the available excavation methods, the NATM (New Austrian Tunneling Method and the TBM (Tunnel Boring Machine) are the most used (STUVA, 2016). NATM is the most commonly used method for manual excavation. The technique uses mass observation to determine what support is needed. This results in a small lining thickness, optimizing the cost of this activity. In general, the lining is done with sprayed concrete, and can yet receive additional surface finishing. NATM is considered a cheap good option, but with low progress rates.

Many efforts were made for the mechanization of tunnels, usually emphasizing excavation capacity. In order to achieve this goal, the TBM concept was designed to excavate the material ahead of the machine using a rotating cutting head. This has been a very adaptable technique since it can deal with excavations of soils, rocks and even the conjunction of these two materials. The lining mostly used along with this technique is precast concrete segments.

2. TUNNELLING EXCAVATIONS AND LININGS

Tunnelling is considered complex and costly by the society. For this reason, people to establish new means of execution of a project, so that it has a smaller financial impact. There is a tendency in engineering to search for less costly and faster methods to perform tasks.

Maidl et al. (2012) describe many of these efforts in a review of mechanised shield tunnelling. These authors comment on the advantages and challenges of using a TBM to exacavate tunnels. The choice of lining along with the TBM usualy is precast concrete segments.

Tunnel lining is an expensive element. The volumes of projected concrete or even the precast segments cost significant sums of the project overall. Any improvements would have a positive impact on these works, either finishing in a shorter time or evenly saving money.

It is necessary that the lining activity has an efficiency similar to that of the excavation front. If there is a delay in the lining, it may become a bottleneck of the excavation process. Here it is noticed that in the case of NATM, the low productivity is due to having to stop daily activities (due to the explosions) and high time of preparation of the excavation front.

Since the 1960s, the use of extruded concrete as a lining method has been studied. There was a development of methodology and use of the method in Europe and Japan. Some authors comment this lining methodology. The book by Kolymbas (2005) describes how promising, but still leads to deepening.

Fukuchi (1991) has described the development of the extruded concrete lining in a renowned magazine covering tunnels. His recommendation would be that this method could replace other linings on many occasions.

This method has been applied in tunneling projects in Japan. A new way of lining the tunnel was suggested, unlike the solutions that were on the market. The method of combining extrusion with the NATM excavation was used in some tunnels, being awarded by JSCE in 2012 as an excellent engineering achievement (JSCE, 2012). This alternative was called SENS and will be described ahead. The name combines the methods used (Shield, Extruded NATM System).

The article by Royal et al. (2010), we describe a numerical analysis of a tunnel excavated with a TBM, but with extruded concrete lining. Two types of concrete are analyzed (normal concrete and polymers) to determine if their hardening time will impair excavation performance. The authors emphasize that polymers can be used as lining, achieving better resistances of the support. Their opinion also is that this lining can replace pipejacking and precast in many ocasions.

3. EXTRUDED CONCRETE LINING (ECL)

A new method has been developed since the late 1960s as an alternative to other linings. Zinevich and Pogrebinskii (1971) presented some of the earliest development efforts of the extruded lining for tunnels, arguing that labor costs could be reduced by 50 percent. Foster-Miller Associates (1979) did a long research on the feasibility of extrusion method since it was characterized as a review of the state of the art.

Extruded Concrete Lining (ECL) has been developed in order to achieve a faster advancement in the tunnel finish, which can be demonstrated as a cheaper technique. The sliding shape follows immediately after the cutting head of the drill, aiding the placement of the concrete in its final shape. The choice between reinforced concrete, unreinforced concrete, fiber reinforced concrete or other methods is done according to soil conditions.

Throughout the years of description, some tunnel projects have adopted this type of lining, being used for transportation, sewage and electricity projects. Some of the examples of projects that used this technique are listed in the following table. Extrusion is a continuous lining process where a material will be confined in a matrix, thereby acquiring its shape. A thread is used to force the material through an extrusion die to form the desired material, in this case the tunnel liner. The rotation speed of the thread is used to control the filling of the compaction chamber.

Table 1 – Project that used ECL

Year of construction	Location / Tunnel purpose	Lining	Soil type
1967/68	Nagoya Drain	Steel-bar reinforced concrete	Sand and gravel layer
1976/77	Prague Metro	Plain concrete	Slate layer
1978/79	Hamburg Sewer	Steel fiber concrete	Water-bearing sand layer
1980/82	Frankfourt Metro	Steel fiber concrete, partial secondary lining	Clay layer
1981	Tokyo Sewer	Steel-bar reinforced concrete	Dilluvial sand layer
1984/87	Lyon Metro	Secondary lining, partially steel-bar reinforced	Sand and gravel layer
1985/86	Freudenstein Pilot Tunnel	Plain concrete	Gypskeuper
1988	Essen Metro	Fiber reinforced concrete and part of secondary lining	Silt layer and marl
1988/89	Shinanogawa Water Tunnel	Plain concrete	Sand and silt layer
1992	Milan Subway	Concrete	
1994	Okanami	Fiber reinforced concrete	
2004/10	Sanbongi Hara Tunnel	Concrete	Loose sand and clay
2011	Tsugaru-Yomogita Tunnel		Diluvial loose sand

Source: Fukuchi (1981) and Chishiro (2011) adaptaded

Some studies have suggested that there are advantages points used in the extruded concrete, compared with staining techniques, NATM and pipejacking.

Fukuchi (1991) mentioned that precasted concrete segments is costly not only due its unit price. It is necessary to build the factory in an already urbanized place, transport the segments within the city to the temporary work place and subsequently take them to the excavation front. The author also discusses some advantages such as better sealing, elimination of the grouting activity and even suppression of the secondary lining.

Konishi (2016) cited a comparison of the NATM and concrete extrusion methods, with the Sanbongi Hara tunnel as an example. He reports that the NATM technique was used for sand excavation with low cohesion. The excavation methodology was changed to TBM with extruded concrete after two face collapses.

Royal et al. (2010) describe the extruded lining as an alternative for microtunneling. In small diameters (d <1m) the pipejacking technique is used. This technique is useful, but it cannot reach distances much greater than 500 meters without a visit well. The friction of the tunnel walls is so great that it can break the rings in these situations. In addition, large-diameter tubes cannot be done with this technic.

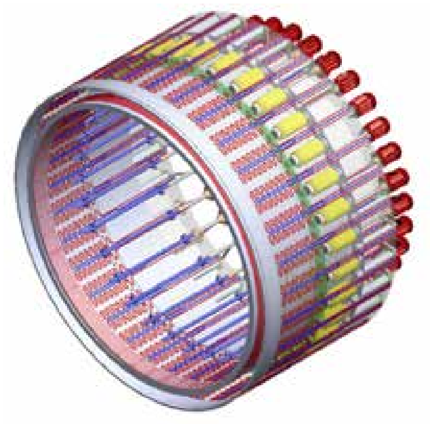
3.1. BraBo Technology

BraBo (Brazilian Borer) is a laboratory that provide solutions to the tunnelling market, based in Palhoça, SC, Brazil. The company is a developer of technologies in the area of geotechnics, with the aid of research projects and private clients. The entity researches topics such as concrete extrusion, which will be presented its study, still under research.

The choice by BraBo of a material other than conventional concrete for the extrusion of the lining was for two reasons. It was desired to use a sliding formwork and also to obtain a higher strength.

The extrusion process is hardly used in civil engineering when compared to the most common cement, concrete. The concrete mixture has a much simpler rheology, usually with a low control of the element used.

Picture 1 – Extrusion nozel



Source: Noronha (2014)

Extrusion is a process that has a much more refined control of materials. Some technological innovations have facilitated this fine rheological balance. The addition of dispersers, hydrophilic fibers, rheology modifying agents, more particle size controlled control and a low molecular weight lubricant provided the applicability of the extrusion process to cementitious materials. These components,

together with handle accelerators, allow the early hardening of the final product, maintaining a high compressive strength, being able to reach averages between 70 - 90 MPa.

The figure shows the entire extrusion nozzle around the tunnel. The cement paste is pumped by motors (in red) to the extrusion shell. The cooling system is represented by blue (refrigerated liquid) and red (heated liquid) lines. The yellow pistons will press the mixture to achieve the desired degree of compaction.

3.2. SENS Technology

Recently the extrusion concept was incorporated as an alternative tunnel lining when using the TBM. This new methodology was suggested by Iida et al. (2005) who published, at a congress of excavations on soft soils, on some of the advantages of joining these techniques.

An extruded concrete system was proposed, based on the cast in place technique, but with possible differentials. The technique promises to maintain the productivity of the precast segments facing at a lower cost.

The lining is done using a dismountable formwork that follows the TBM shield, continuously placing a mixture into the void space to serve as tunnel support. The push of the TBM is done over the formwork. This is a fast initial strength concrete gives hardens in a matter of hours, allowing an advance that is consistent with the excavation speed.

The example cited by Iida (2008) was in the Sanbongi Hara tunnel in Japan. Sixteen 1,20 m rings were used as concrete forms. This would leave a total length of 19,2 m.

A machinery was made to aid the formwork activity. The more distant forms of the excavation front are removed, internally transported and reassembled ahead for concrete casting. The figure on the left shows a cross section of the machine, while on the right a photo of the upper section is shown.

This formwork length would be sufficient for about a day of excavation when a minimum concrete strength of 15 MPa was expected. That would be enough to keep safe the excavation and lining.

The extrusion of the concrete would have the advantage of the applied compression rate, being controlled by the pressure of the concrete pumps. This hardening of the concrete under pressure will acquire a better resistance, also decreasing the bending moment.

Some other advantages were noticed when compared to the sliding extrusion system. Note that it would be the least application complexity, since it is not necessary to use the handle accelerator, temperature controls or O-ring systems. This would reduce the number of controls, eventually facilitating the constructive process.

One drawback would be the need for a segment of almost 25 meters form, just behind the excavation head of the TBM. This equipment uses erector arms to perform assembly and disassembly activities. It is a complicated and critical stage of the project.

Hasegawa et al. (2011) suggested that the geology idealized for the use of SENS would be flood soils or other soft rocks, because the rates of excavations are faster than the NATM. However, he points out that SENS has a significantly lower cost than the use of TBM associated with precast concrete lining.

Iida (2008) describes the concept of SENS in his thesis in which he studied the Sanbonogi Hara tunnel, an excerpt from the Japanese train system shinkansen. Initially the tunnel was designed for the NATM excavation. The tunnel was shallow and the geology was loose diluvial sand with a layer of clay. During the excavations, there were two major collapses that made them rethink their method. Soil conditions and practicality led to the choice of safer and faster excavation.

A machine with TBM type shield was chosen, followed by an extrusion formwork. Safety has increased due to the use of the Pressure Balance (EPB) and the progress of the lining. The shield is shown in Figure 18, using a representation of how the front head of the TBM was assembled.

Because they had different methods during the project, they could compare productivity rates on the same terrain and with the same design characteristics. They noticed that the SENS method was more than double for the average monthly productivity (45 m x 110 m) and for the maximum (79 m x 172 m). Konishi (2016) also reported some studies for the same tunnel, arguing that the costs are almost the same as NATM and half of the usual TBM. As the construction work was accelerated, the project was executed in a shorter period of time, leaving a lower cost of maintenance of site camps.

4. DISCUSSION

In this study on extruded concrete we will discuss the advantages and disadvantages of executive methods. Here there will be few moments that will be able to quantify how good would be its use, but will be described qualitatively the differences.

With the use of this lining, it has been noticed that some improvements when compared with other methods. For this reason, some points were separated to be individually discussed, elucidating in greater detail the characteristics of each technic.

4.1. Precast segments fabrication and storage

The segment are precacst concrete elements used for tunnel lining. It is necessary that a large factory be made for the construction of the segments. The production area occupies an area equivalent to a football field. After production, the segments need to be stored until they are transported. This stock area is even bigger than the factory. The whole assembly of production reaches about 30,000 m2.

Production costs go hand in hand with the expressive size and complexity of the plant. Special made molds are required for each segment of the ring. Concrete needs to have a high quality control and its cure is achieved by using a steam chambers. Hoists and cranes are used for moving inside and in the factory yard. Other staging areas of the segments are necessary. A stocking area of one or two days of segments is usually reserved in the tunnel entrace. Other intermediate stock areas may also be used. These ventures are usually in densely populated areas, using beds that usually do not have large areas for these lining stocks.
Sometimes municipality or states provide these areas to assist in the works, reducing the costs of mobilization and maintenance. However, in some cases it is necessary to rent land to make stocks or service areas, costing a reasonable value in the project.

The lack of lining stock area has shown a problem in the Filder tunnel in Germany, quoted by Smith (2016). The stock of parts for placement was limited to 40 segments (complete), which represented a limitation of the process for some times. In this case, it was described that when there was a failure in the operation of the TBM, there was no place to store more manufactured segments.

4.2. Segments road traffic

A study on the transport of the segments to the entrance of the tunnel is important. It is not only the number of segments that impresses. The amount of truck travel from the factory to the tunnel entrance is a challenge in itself.

As an example, we have the case of subway line 4 of Rio de Janeiro described by Montano (2011). The tunnel project was designed with the use of precasted concrete segments in an approximate length of 5 km.

The segments were made in the neighborhood of Leopoldina, and later transported to Ipanema (within 15 km). In this study, it was predicted that 218 truck daily journeys would be necessary in a two-year period only for the transportation of the segments. This represents about 50 trucks making four trips a day exclusively for this transportation.

The route between the factory and the tunnel entrance is quite congested daily. It is a densely populated area with heavy traffic, especially during rush hours. Montano's (2011) study even recommends overnight transportation to avoid traffic barriers, but it is not always possible to stick with this schedule. What often happens is that traffic is hampered throughout the day.

4.3. Inner tunnel transit

The transportation of materials is one of the activities critical to the execution of the tunnel. The choice of tunnel lining will determine the internal transit. Precast concrete segments can be transported with the aid of platform vehicles or small locomotives. The inner part of the tunnel is usually already occupied by the transportation of the excavated material.

One option for transporting inputs along the tunnel is the use of locomotives. These are vehicles that use railway lines to run, so temporary rails are used in construction. Often it is only possible to use a railway line (because of the diameter of the tunnel or because it has not yet been invert), limiting the transport from the tunnel entrance to the excavation front.

The placement of the rails is an activity that requires time and money, as well as cleaning the rails throughout the construction. This is considered as a negative point of this option. There is also a 4% ramp limitation for locomotives (PEEV and SELLMER, 2017). This makes it impossible to use them in very steep tunnels, such as water-borne tunnels for small hydroelectric plants.

Another option of material transport is the transport of segments with MSVs (Multi-Service Vehicles) that use steering cabins at both ends of the composition. This is an improvement because the reversal maneuver inside the tunnel is not required. This type of vehicle can handle slopes up to 25%, larger than those of locomotives. Its setback is that it cannot form a very long composition and can carry few cargo compartments. In some designs, a ring of pre-cast per trip with average speeds of 10 km / h (when loaded) is used.

Both options prove to be slow and costly compared to the extrusion method. In this case, the cementitious slurry is taken from the tunnel entrace to the excavatioun front with MSVs adapted as concrete mixer trucks, obtaining a better productivity in the transport. For each trip, it is possible to take 6 m3 of concrete up to the facing front.

The truck is smaller, facilitating maneuvers in places with few areas for maneuver like tunnels. The speed is higher with this type of equipment reaches 25 km / h loaded, saving the transport time of the lining inside the tunnel. This represents about twice the speed when compared to MSV for segment transport.

4.4. Assembly method

Placing concrete segments requires tremendous effort. Each piece weighs almost a ton and should be placed in different positions along the tunnel. An erector is used which positions each of the segments in their proper position. This machine is composed of a rotor arm and a system of suction cups that lift the parts in a vacuum.

This is a type of sophisticated and expensive equipment. The machine is one of the fundamental elements of the excavation process. It needs to work at almost the same speed as the cutting head. Once the positioning is completed, screws are attached to secure the adjacent segments. Grouting is also necessary for completion.

4.5. Support thickness

The thickness of the lining depends on the stresses (and other functions) to be supported. In the case of TBM with precast lining, the thickness of the segments must be determined for the worst soil situation of the entire section to be executed. There is only one template to be executed during a project, and no differences can be made between the size of the segments.

The difference in thickness of the support wall can be seen in the different execution methodologies. Taking notice of the classification of Bieniawski (1989), it is perceived that the maximum thickness is of 20 cm for cases of very bad rock. For the concrete segments, the average thickness is at least 30 cm. This can represent less than 50% of concrete for lining, which represents a very large difference in terms of final construction cost.

We can illustrate by comparing the lining thickness of a 10-meter diameter tunnel (it is one of the measures most used by Bieniawski (1989)) in the NATM and precast methods. This was the solution used in the tunnel for high-speed trains used in Florence.

Raschilla and Severi (2012) described the characteristics of this tunnel, as it uses geology of alluvial soils and clay. A 40 cm thick pre-cast lining was adopted. For the same segment, concrete could be adopted with only 15 cm of thickness, according to Barton's classification. This represents a reduction of 62.5% of the concrete applied.

When we apply the reduction to the entire length of the tunnel, we can see the size of the economy. Each concrete segment is 1 meter large, using about 10 m3/m. Throughout the 5,000-meter tunnel, 50,000 m3 of concrete will be used, a fairly reasonable amount. If the options of sprayed concrete and extruded concrete were chosen, the total volume would look like 18,750 m3.

The cost of construction with the SENS methodology is also lower than if precast segments are used. Akaji (2017) describes that this methodology was used in some tunnels in Japan, obtaining results of lining costs that resemble those of projected concrete, notoriously smaller than that of precast segments.

4.6. Progress rates

Toma (2005) describes the NATM as a cheap method, since it minimizes the need for support of the linig according to the soil / rocks. This may prove economical for various types of contracts. Otherwise, it describes its weaknesses as the speed of progress. According to the classification and method of Bieniawski (1989), the maximum daily advances without support are 3 meters in excellent conditions of rock, in a diameter of 10 meters. When we compared the NATM's 3-meter speed of progress with the 30-meter TBM, we realized a major disadvantage in terms of time spent for excavation.

Ehrbar (2008), chief engineer of the Saint Gotthard tunnel, demonstrated this. For this case, more than 57 km of double tunnel were excavated, using various technics and progress rates. The NATM solution showed daily average advances of 1 meter per day, while TBM achieved 11,3 m on average. It was reported that with this last technology, the daily productivity was up to 56 meters (HERRENKNECHT, 2012).

4. CONCLUSION

Concrete extrusion has been considered as an innovative method of tunnel lining. In the mid-1960s, it was developed as it was hoped to be a faster and cheaper method. Recent application in some tunnels has continuously evolving to have a simpler operation.

This methodology in tunnels with the objectives of achieving safety, better rates of progress and economy (monetary and time). Some studies have validated their resistances and performances using numerical simulation and executed projects (observations).

Two machines for ECL were presented, describing its components and characteristics. The first would be a sliding model with a very fast process of hardening the cementitious paste. The second model was a system of collapsible forms that cover about one day of lining works.

Aspects of production, logistics, permeability, ease of construction and costs were presented and discussed individually. The comparisons were compiled in Table 2, in order to make easier to demonstrate the positives and the ones that could lead to improvements.

Table 2: Different methods approach

	NATM	TBM	SENS
Lining	Sprayed concrete	Precast concrete segments	ECL
Lining production	Inside the tunnel, with pressurized hoses	Precast segments factory	Inside the tunnel, using formworks
Lining resources storage	Tanks (small areas)	Stockyards and tunnel entraces (big areas)	Tanks (small areas)
Road transportation	Only the lining resources	Daily transportion of precast segments	Only the lining resources
Assembly method	Sprayed concrete	Erector arm	Formwork
Lining thickness	Small (up to 15 cm)	Large (30 to 80 cm, possibly even thicker)	Medium (15 to 30 cm)
Costs	Low	High	Medium
Progress rates (m/day)	< 3	20-35	20-35
Safety	Excavation front has elevated risk of collapsing	Exavation fron is soon covered by the shield and lining	Exavation fron is soon covered by the shield and lining

Source: Silva, 2017.

The study points out that ECL may be more economical than other tunnel lining methods. The technique was even awarded by JSCE (Japan Society of Civil Engineers, 2012) as an outstanding engineering achievement that year due to its innovations and improvements.

A numerical simulation of a project may be the result of future research. Although it has already been described by Royal et al. (2010). It can now be applied to other tube diameters. Some topics such as improved bending moment and water sealing can be added.

Simulations can compare material quantities, performance and costs when different methods (NATM, TBM and ECL) are applied. A better detailing on an extrusion system could lead to having an equipment budget. This would facilitate the generation of a cost comparison between the methods.

The application can be achieved through partial objectives, as the making of pieces in plates and shells. Molds, such as concrete galleries or wood forms, may be used. With a casted piece, it is possible check what the resistances that were achieved.

The application can be realized through partial objectives, as the making of pieces in plates and shells. One imagines that one can use molds, like concrete galleries or formwork.

This method can be applied in a tunnel. This only for research purposes or even on a microtunnel (diameter <2m). The costs for these cases may be much lower when compared to a large-diameter sections.

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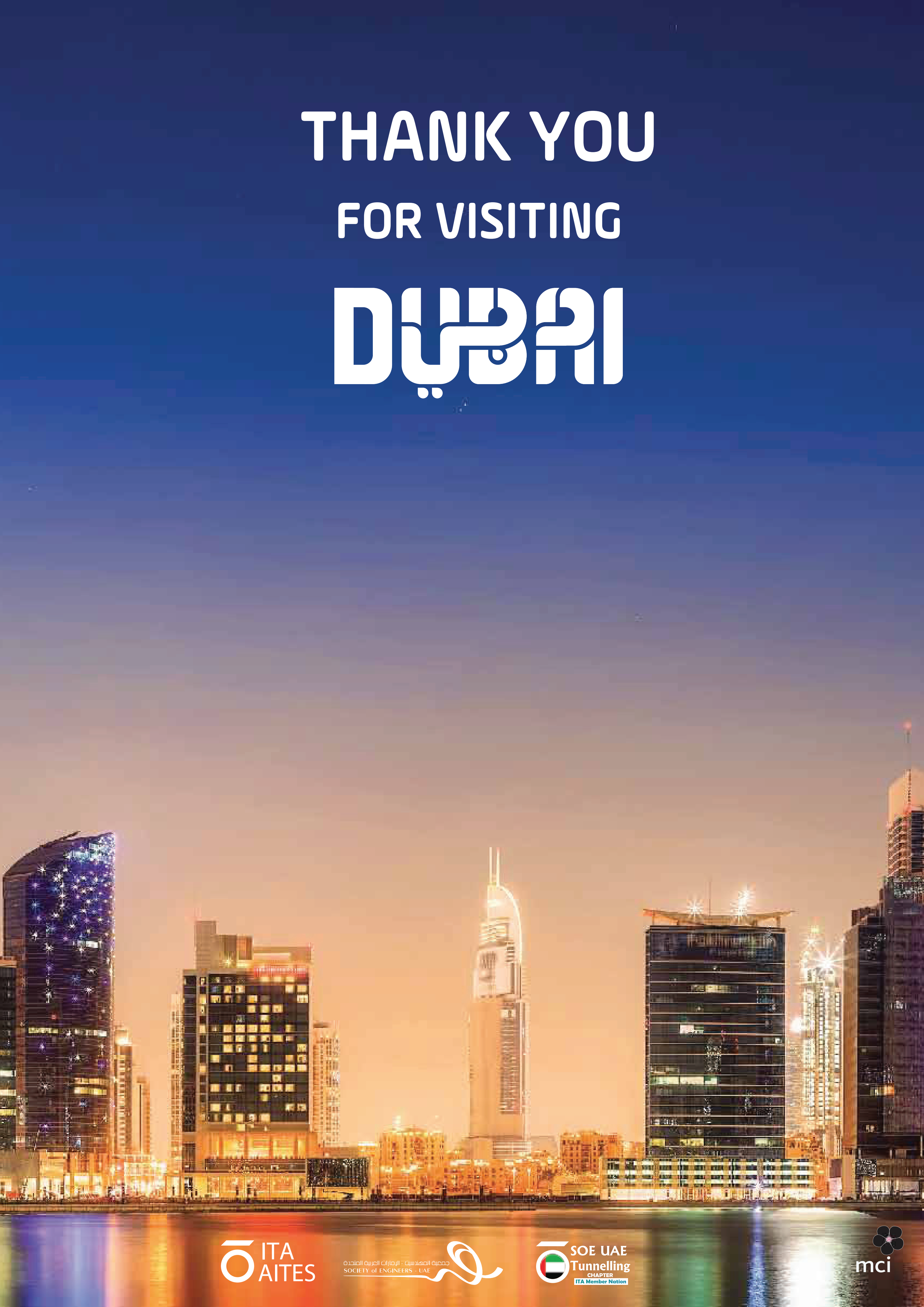
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