Chapter

Innovative Concepts in TBM Tunnels

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Abstract

Tunnel boring machine (TBM) tunnels are increasingly used in the construction of transport infrastructure, allowing for reduction of the environmental impact and cost and time of construction. Despite these advantages, TBM tunnels still face major challenges such as further cost reduction, the structural safety under earthquakes, and the improvement of safety during operation in the case of traffic tunnels (rail and road tunnels). To overcome these challenges, three innovative and very cost-effective concepts for the construction of TBM tunnels were recently developed by the author: the tunnel of improved seismic behavior (TISB) concept for improving structural safety of tunnels on soft ground in seismic areas and the tunnel multi-floor (TMF) and tunnel multi-gallery (TMG) concepts for road and rail tunnels, respectively, which allow an even greater cost reduction and improvement of safety in operation. In this paper these concepts are presented as well as their application in some specific cases, emphasizing the obtained added value.

Keywords: tunnels, TBM, innovations, TISB, TMF, TMG

1. Introduction

Tunnels are increasingly used in the construction of traffic infrastructure for both rail and road networks.

The "tunnel boring machine" (TBM) technique is nowadays the most common, allowing for reduction of the environmental impact (in underwater tunnels allows for non-disturbance of the natural bed) and significant savings in costs and time. It has become usual to build more than 0.4 km of a TBM tunnel per month on average, depending on the specific ground conditions.

Despite great progress observed in recent times, the construction of traffic (rail and road) tunnels with the TBM technique still faces significant challenges.

Big issues are the improvement of the structural safety of the tunnels when built in soft ground in seismic areas, the decision on the number of separate tubes to form the tunnel with cost analysis, and the measures to provide safe evacuation of users in the event of an accident or fire inside the tunnel.

2. TBM tunnels

In the construction of tunnels bored with TBMs, the circular cutter head of the front shield of the machine excavates the ground as the erector mounts precast

Figure 1.
Schematic view of a TBM.

segments around the excavated surface, which are clamped together, forming the circular wall (lining) of the tunnel (**Figure 1**). TBMs are of different types, depending on the characteristics of the ground to be bored (EPB, mix-shield, hard rock, etc.) [1].

The precast segments are made of high-strength concrete (C40 or higher), reinforced with steel bars or fibers (in steel or synthetic). The number of precast segments in each ring will be appropriate to form complete circles with pieces of a given weight, according to the capacity of the handling equipment; commonly medium size tunnels have 6–8 segments per circle. The thickness of the precast segments will depend on the surrounding acting stresses and on the thrust forces applied by the TBM; in common situations it corresponds to about 1/25 of the internal diameter of the tunnel.

After the execution of the tunnel wall, a fill is installed at the bottom of the tunnel, creating a platform for the circulation of the vehicles: trains in the case of rail tunnels or cars and trucks in the case of road tunnels.

3. Challenges

As is known, the TBM technique is suitable for the construction of tunnels in stiff ground (rock, stiff clay, compacted sand, etc.), since the tunnels built in this way have their stability ensured by the resistance of the surrounding ground (the precast segments mainly work as a finish), so they do not need to have significant resistance in both the transverse direction and the direction of the tunnel axis.

In the case of soft soil (mud, soft clay, loose sand, etc.), the TBM tunnels can be unreliable because, as the connections between precast segments are very weak (it is a kind of LEGO), the strength and the ductility of the tunnels are low, so there is a risk of sinking, even collapsing, particularly during earthquakes. Soil treatments, sometimes used to aid seismic behavior, are very expensive and often do not guarantee the reliability required for the tunnels.

Regarding the number of tubes, in the case of rail tunnels in order to meet the international safety requirements [2, 3], the installation of both directions of traffic placed side by side in the same tube is only possible in short tunnels.

In long rail tunnels (tunnels over 1 km in length), for safety reasons [2, 3], two separate tunnels are usually be built, each for a direction of traffic, and a complex system of cross-passages connecting the two tubes. In the event of an accident or fire inside the tunnel, users will leave the affected train and move to the other rail gallery to be rescued later by another train. In some situations systems of safety galleries and shafts are also built for local access of the emergency personnel.

As an example, the Gotthard Base tunnel (recently built in Switzerland), with 57 km in length, the longest in the world, is formed of two tubes [4]. Cross-passages regularly spaced along the tunnel and access galleries to outside in some locations were adopted (**Figure 2**).

Where it is not possible to build access galleries or shafts (e.g., in underwater tunnels), three tubes are usually adopted. This is the case of the Channel tunnel (between the UK and France) or the basic layout of the Gibraltar Strait tunnel, where two tubes are used for rail traffic and a third tube, placed between the two, is used for access to emergency services and rescue of users, using special vehicles with wheels (**Figure 2**) [4]. The three tubes are also interconnected by a number of cross-passages, regularly spaced.

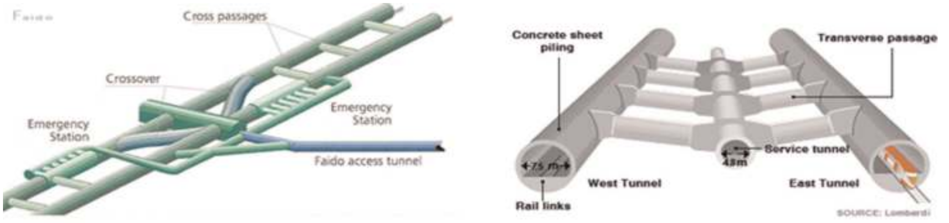
Also in the case of road tunnels, the installation of the two traffic directions in the same tube is only possible in tunnels with a single lane in each direction. When there are two or more lanes in each direction, the required diameter of the tunnel would become so large that it would be impractical. In any case, in long road tunnels (longer than 0.5 km in length), in order to satisfy safety requirements [5], placing bidirectional traffic side by side in the same tube is quite problematic. Hence, two separate tubes, each one for a direction of traffic, are nowadays usually built, so that, for ventilation and smoke removal purposes, air will circulate in one direction, the direction of traffic.

Generally, the two tubes are interconnected by cross-passages, regularly spaced, so that in the event of an accident or fire, users will leave the incident tube to the other, from where they will be evacuated by conventional buses, such the Westerschelde tunnel, in the south of the Netherlands (**Figure 3**) [6].

Where possible, instead of cross-passages, access galleries and evacuation routes are built along the tunnel, to allow local access and evacuation of users from the tunnel. This is the case of the tunnel of the south bypass of the M30 motorway, in Madrid, Spain, in which two large diameter tubes were adopted (**Figure 3**) [6].

Building of two (or three) tubes and the systems of cross-passages or access galleries makes the construction of the tunnels very expensive. In addition, although such layouts represent the most advanced solutions at present for rail and road tunnels, the long time necessary for rescue services to reach the scene may be too long, as has been seen in the recent past.

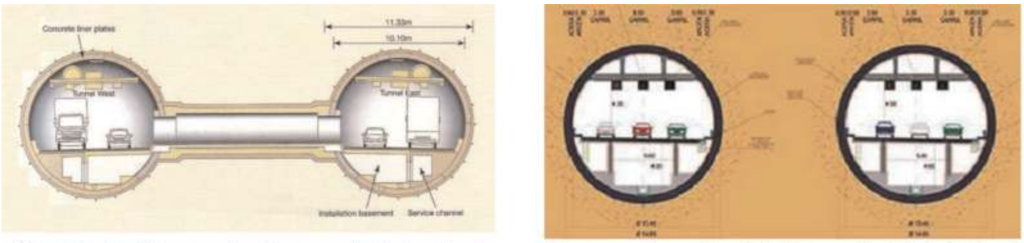
In order to overcome the abovementioned limitations, the tunnel of improved seismic behavior (TISB) concept for TBM tunnels on soft ground in seismic areas



Gotthard-Base tunnel

Gibraltar Strait tunnel (Basic lay-out)

Figure 2.
Common layouts of rail tunnels.



The bi-tube Westerschelde tunnel, Netherlands

The two tubes of the M-30 tunnel in Madrid, Spain

Figure 3.
Common layouts of road tunnels.

and the tunnel multi-gallery (TMG) and tunnel multi-floor (TMF) concepts for TBM rail and road tunnels, respectively, were recently developed.

4. The TISB, TMG, and TMF concepts

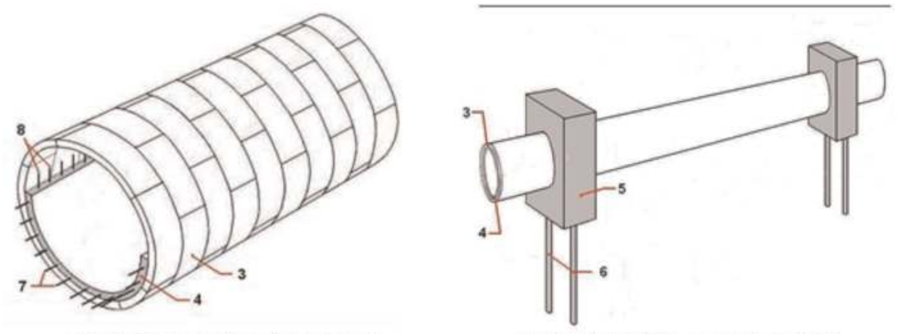
4.1 The TISB concept

The "tunnel of improved seismic behavior" concept is an innovative solution for TBM tunnels, when the referred tunnels are built in soft ground (e.g., mud) in seismic areas, allowing the tunnel to be provided with the adequate resistance and ductility. It also allows the strengthening of existing TBM tunnels, using them as external formwork for the execution of the internal strengthening [7]. The TISB concept is a Portuguese patent [8] and is illustrated in **Figure 4**.

In the TISB concept, the tunnel is formed by two concentric tubes; an external tube (3), which is a conventional TBM tunnel, and an internal tube (4), which is subsequently executed, inside the external one. The external tube (3) is thus formed by precast segments mounted by the TBM, while the internal tube (4) is later cast inside the external tube (3), using the latter as exterior formwork. Within the thickness of the internal tube (4), longitudinal reinforcement bars (7) and transverse reinforcement bars (8) are laid, both in two layers, which are confined by confinement bars, so as to provide the tunnel with adequate strength and ductility.

Where the vertical actions in the tunnel can have a significant variation (e.g., due to the increase or decrease in the height of the overburden in underwater tunnels), the tunnel will be provided with supports, regularly spaced along the tunnel axis. Those supports are composed of groups of piles with great horizontal deformability and ductility, arranged in the longitudinal and transverse directions, which are anchored at the top in large blocks of jet grouting (5) surrounding the outer tube (3) and at the base in the stiff ground below, so to resist vertical loads, while allowing horizontal movements of the tunnel during earthquakes, functioning as a kind of "movable bearings."

The TISB concept thus leads to the obtaining of monolithic structures (there are no joints) with appropriate resistance in both longitudinal and transverse directions and great ductility under earthquakes. It will also be very effective if liquefaction and cyclic mobility phenomena occur. In addition, the structures obtained will present great structural redundancy, which can be useful in the case of unforeseen scenarios during the design phase.



Detailed perspective of the tunnel

Perspective of the complete solution

Figure 4.
Illustration of the TISB concept.

4.2 The TMG concept

The “tunnel multi-gallery” concept allows, with a single TBM tunnel, the creation of rail tunnels with completely independent directions of traffic and the installation of appropriate means that provide a dedicated and very reliable system for local access of the emergency personnel and the evacuation of users, in the event of an accident or fire inside the tunnel. The TMG concept is a Portuguese patent [9] and is illustrated in **Figure 5**.

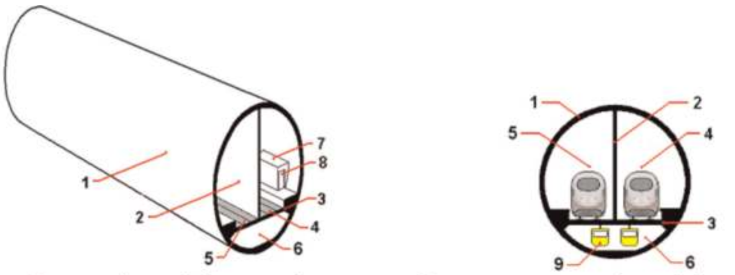
In the TMG concept, the tunnel is constituted by the external wall (1) made by the TBM, a slab (3), placed slightly above the bottom of the tunnel and the entire width, and a separating wall (2), placed in the middle of the tunnel and its entire height, so as to form two independent rail galleries, disposed side by side (4) (5), one for each track, and a service gallery (6) below.

In both sides of the tunnel, vertical access galleries (7), regularly spaced and provided with escape doors (8) in both rail galleries, are also created, allowing for the safe passage of people to the service gallery (6), in the event of an accident or fire inside the tunnel. Inside the service gallery (6), emergency vehicles (9) of monorail type are installed, to provide local access to the emergency personnel and the evacuation of users to outside.

A variant B of the basic solution may also be adopted, in which the vertical access galleries (7) are placed in the middle of the tunnel, in the separating wall (**Figure 4**). Although there is a local slight reduction of the cross-section of the rail galleries, it avoids the need to make openings in the external wall of the tunnel.

4.3 The TMF concept

The “tunnel multi-floor” concept allows with a single TBM tunnel the creation of road tunnels with two identical road galleries, isolated and independent, and the installation of appropriate means that provide a dedicated and very reliable system for local access of the emergency personnel and the evacuation of users, in the event of an accident or fire inside the tunnel. The TMF concept is a Portuguese patent [10] and a European patent [11] and is illustrated in **Figure 6**.



Perspective of the tunnel

Current cross-section of the tunnel

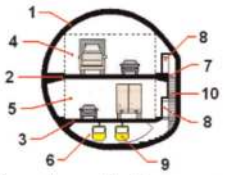
Cross-section at vertical access galleries

Cross-section at vertical access galleries- Variant B

Figure 5.
Illustration of the TMG concept.

Perspective of the tunnel

Current Cross-section



Cross-section at vertical access galleries

Figure 6.
Illustration of the TMF concept.

In the TMF concept, the tunnel is constituted by the external wall (1) made by the TBM and two slabs (2) (3), built at its full width, one placed roughly at half the height of the tunnel and the other placed slightly over the bottom of the tunnel, so as to form two superimposed two road galleries (4) (5), one for each direction of traffic, and a service gallery (6) below.

In one of the sides of the tunnel, vertical access galleries (7), regularly spaced and provided with escape doors (8) in both road galleries, are also created, allowing for the safe passage of people to the service gallery (6), in the event of an accident or fire inside the tunnel. Inside the service gallery (6), emergency vehicles (9) of monorail type are installed, to provide local access to the emergency personnel and the evacuation of users to outside.

4.4 Specific matters

The application of these new concepts in the construction of traffic tunnels raises specific issues that require the adoption of appropriate measures.

Tunnel cross-section. Regarding the rail tunnels, the internal diameter will depend basically on the speed of the trains and the permissible pressure variation inside the trains. **Figure 7** shows relationships between the cross-section of the rail galleries of bi-tube tunnels and the permissible pressure variation inside trains of 12.4 m^2 of the front area (a common value in high-speed trains), for different speeds of the trains [12].

Admitting as acceptable a pressure variation of 5.5 kPa (appropriate value since there is no clash of the piston effect of the trains), for example, for speeds of 300 and of 250 km/h, cross-sections of 52 and of 38 m^2 will be required, respectively, in each railway gallery.

However, as this effect is only sensitive in the portal zones of the tunnel (at the entrance and exit of the trains), it can be overcome by adopting special arrangements in those zones, namely, creating openings in the separating wall, whose area decreases from the outside to the inside, acting as pressure relief (**Figure 8**), which allows a significant reduction (10–15%) of the cross-sectional area of the railway galleries [13].

When variant B of the TMG concept is used, the placing of the vertical access galleries in the middle of the tunnel will cause slight localized decrease of the

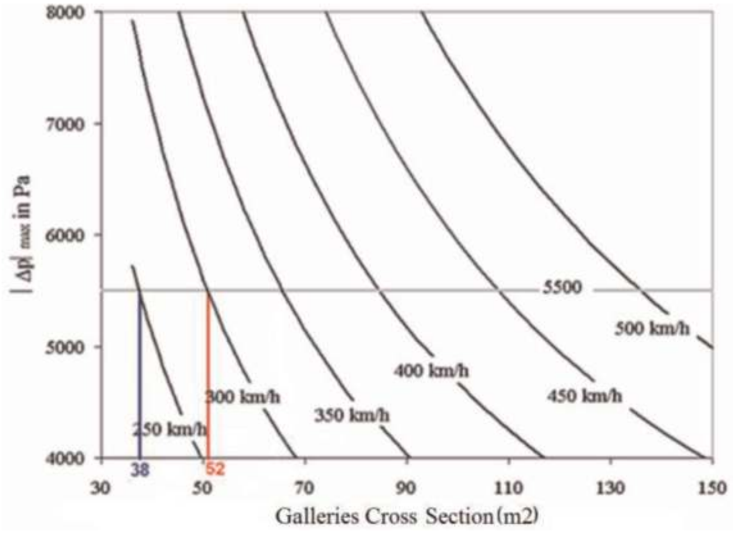


Figure 7.
Relationships between the cross-section of the rail galleries of the tunnels and the speed of the trains.

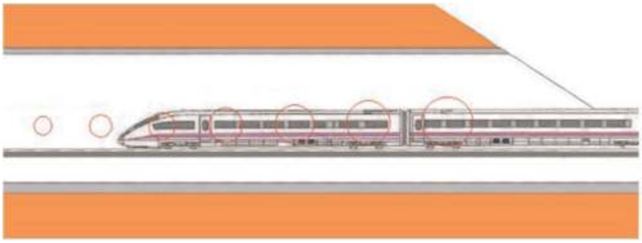


Figure 8.
Openings in the separating wall at the portal zones of the tunnels.

cross-sectional area of the railway galleries on those areas and thus an increase in the pressure variation inside the trains. However, as the vertical access galleries are inside the tunnel, outside the portal areas, this has no influence on the comfort inside the trains.

Regarding the road tunnels, the internal diameter will depend essentially on the number of lanes in each traffic gallery and their width and the permitted height of the vehicles. In Europe, where the height of the vehicles is limited to 4.0 m, a minimum clearance of 4.8 m will be, in general, adopted.

Execution of vertical access galleries. When the vertical access galleries are placed on the external wall of the tunnel, they will be built by locally dismounting the precast segments mounted on those areas and casting new concrete walls in situ.

In situations where there is water pressure around the tunnel, injections of cement grout will allow for the development of the works in safe conditions. In those situations special steel segments will be mounted on those areas, provided with holes to allow for the execution of the injections.

Although there are some risks, they are similar to those of execution the cross-passages in twin-tube tunnels.

Firefighting. The traffic galleries of the tunnels will be equipped with active detection and attack devices, acting jointly, instead of relying on conventional systems of attack by fire trucks. Heat sensors and smoke detection systems automatically activate high-pressure water mist nozzle systems, regularly distributed along the tunnel and grouped in sections, lowering the temperature on site. After this action, firefighters (who come through the service gallery) can then extinguish the fire.

Rescue of users. In the event of an accident or fire inside one of the traffic galleries of the tunnel, users will leave that gallery through the emergency walkways to the nearest escape door, from where they reach the service gallery below, down the stairs inside the vertical access galleries. Inclined platform lifts running along the stairs provide access to handicapped people.

Emergency vehicles of the "emergency monorail electric vehicle" (EMEV) type that circulate inside the service gallery will rescue the users to outside of the tunnel.

Emergency vehicles. The EMEVs are autonomous vehicles that receive wireless signals from the tunnel control center. They are battery powered, so as not to be dependent on the reliability of the electricity network inside the tunnel. They circulate suspended from the ceiling slab, in general, in two parallel lines. They are grouped in "trains," in numbers according to the needs. They will be parked at one or both of the tunnel portals, where users will have outbound exits.

5. Application of the TISB and TMF concepts on a proposal for a road tunnel crossing the Tagus River in Lisbon

5.1 Introduction

The Algés-Trafaria road tunnel, crossing the Tagus River in Lisbon, Portugal, aims the decongestion of the road traffic of the suspension bridge, which is currently 50% higher than its capacity. It will allow the closing of the inner ring motorway of Lisbon, constituted by the CRIL in the north bank, the Vasco da Gama Bridge at east, and the CRIPS (A33) in the south bank of the river. It will be located west of the suspension bridge (**Figure 9**).

The location of the tunnel is characterized by the existence of thick alluvial deposits along the riverbed, composed of various complexes of mud and sand, extending from elevation −29 m (the deepest level of the river) to elevation −75 m. Underlying the alluvial deposits, there are bedrock formations constituted by basalt and limestone that extend by the north bank. On the south bank, there are Miocene

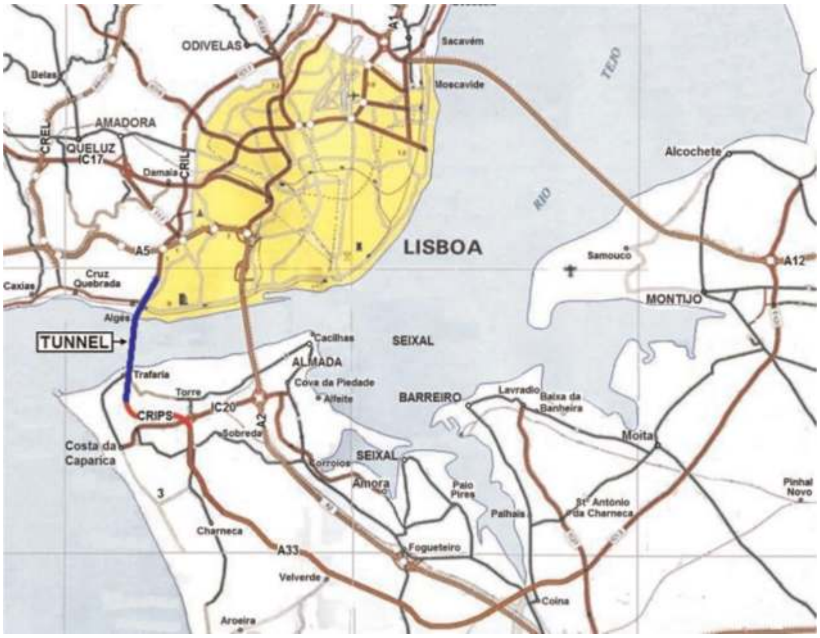


Figure 9.
Location of the Algés-Trafaria tunnel crossing.

formations composed mainly of sand and clay. The very prone-seismic conditions of the area must also be noted (one must remember the 1755 Lisbon earthquake, one of the most destructive in history).

Preparations for the construction of the new crossing have been under way for a long time, and an immersed tunnel solution has already been studied by Lusoponte, the concessionaire of the Tagus road crossings in Lisbon [14]. However, for various reasons, no significant progress has been made.

The study concluded that the construction of the immersed tunnel is viable but presents significant risks, associated with the high probability of liquefaction of the sands that constitutes the riverbed, in the event of a strong earthquake, and also with the difficulties of the realization of the tunnel connections at its ends, which will significantly increase the overall cost of the project. The cost of the tunnel (at current prices) was estimated at 600 million euros.

A TBM tunnel solution for the crossing, based on TISB and TMF concepts, was, in the meantime, proposed by the author [15–20].

5.2 The proposed TBM tunnel solution

In the proposed solution, the tunnel will be a single-tube tunnel, 5.1 km in length with two superimposed road galleries and a service gallery at the base. At the deepest part, the bottom of the tunnel is at elevation −59 m, allowing for a soil overburden identical to the diameter of the tunnel. The tunnel runs through the alluvia along most of its length under the river (**Figure 10**).

The tunnel has an internal diameter of 14.2 m, with precast segments 0.55 m thick (Di/25) and 0.15 m clearance between the lining and the ground to be injected with grouting; hence, the excavated diameter of the tunnel is 15.6 m.

Despite the large diameter of the tunnel, it is significantly smaller than that of the larger tunnels being built, such as the SR99 in Seattle (USA), with a 17.5 m diameter, and the Tuen Mun-Chek Lap in Hong Kong (CN), with a 17.6 m diameter.

Inside the tunnel two concrete slabs are built, in order to create two superimposed road galleries (each one for a direction of traffic) with two lanes each (3.5 m wide and 4.8 m high); outer emergency lane; inner edge and emergency walkways on both sides, with a total width of 12.6 m; and a service gallery at the bottom, 2.0 m high (**Figure 11**).

To provide the tunnel with adequate structural safety under earthquakes, the section under the riverbed (2.25 km long) will be strengthened with an internal reinforced concrete tube 0.3 m thick, dully confined, in order to improve its strength and ductility, which are essential in the case of liquefaction of the sand (**Figure 11**).

The upper slab is supported laterally on continuous corbels executed in the precast segments or cast jointly with the internal tube (where it exists). The lower

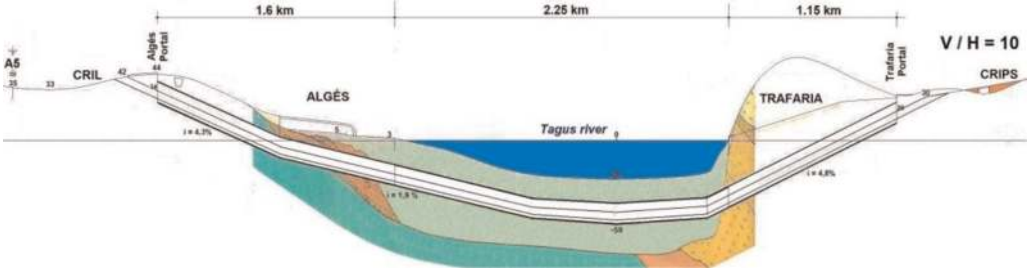
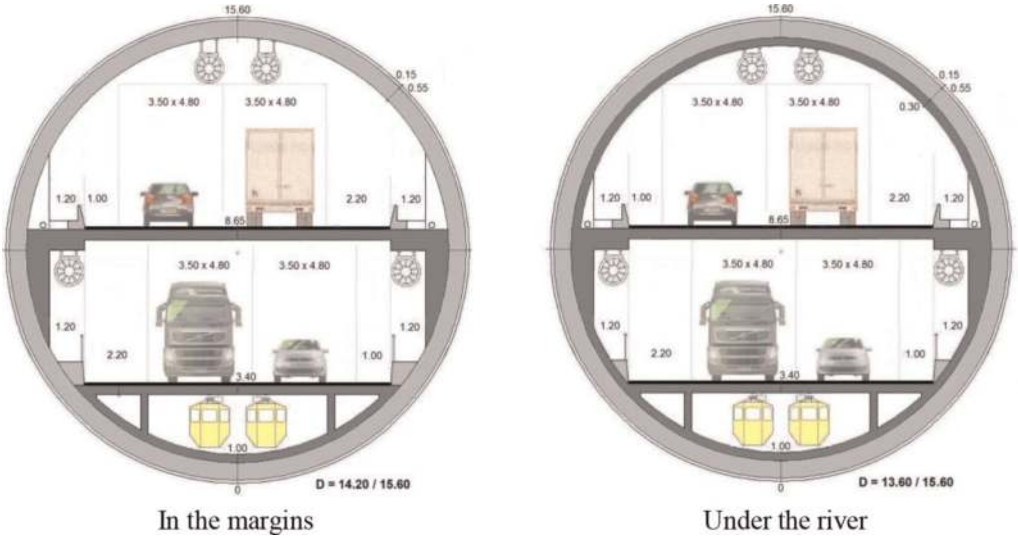


Figure 10.
Proposed TBM tunnel solution for the Algés-Trafaria crossing. Longitudinal section.

slab is supported on two small longitudinal concrete walls cast in situ and on the TBM tube.

The road galleries have escape doors located on one side of the tunnel, spaced 400 m (less than the 500 m allowed by the EU rules) [5], which give access to the service gallery below, through vertical access galleries with 2.6 × 3.5 m of inner section (**Figure 12**).

Inside the service gallery, emergency vehicles of the EMEV type circulate to allow for the access of emergency personnel to inside the tunnel and the evacuation of users out of the tunnel in the event of accident or fire.



In the margins

Under the river

Figure 11.
Proposed TBM tunnel solution for the Algés-Trafaria crossing. Current cross-section.

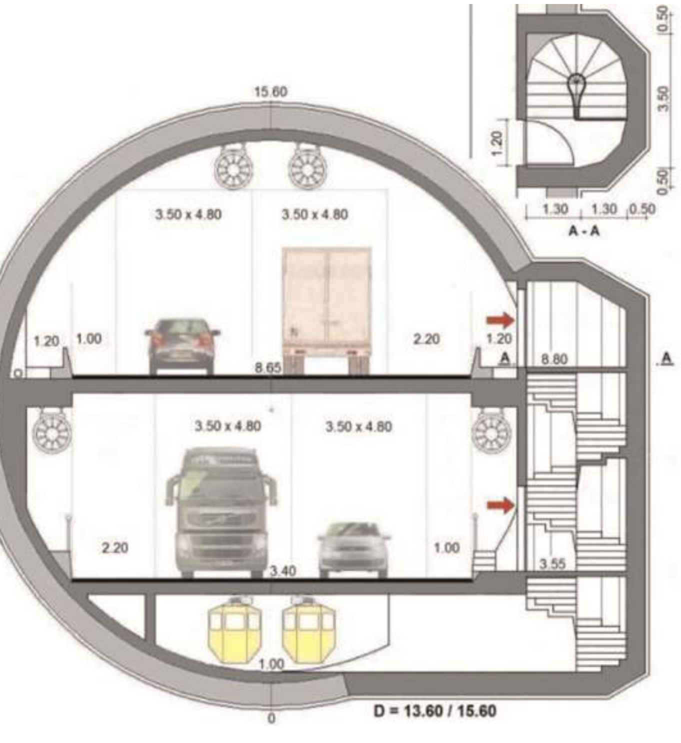


Figure 12.
Proposed TBM tunnel solution for the Algés-Trafaria crossing. Cross-section at vertical access galleries.

Environmental impact. Once the tunnel is bored by a TBM, its construction will not cause any disturbance of the riverbed along the tunnel axis. Traffic on the Tagus River and on the port of Lisbon will not be disturbed either. The connections of the ends of the tunnel to the existing road network, on both sides, present no particular difficulties.

Safety in operation. The tunnel is provided with an advanced safety concept, which represents a step forward in the safety of road tunnels.

In the event of an accident or fire in one of the road galleries, users will leave the incident gallery by walking through the respective emergency walkways to the nearest escape door, from where they reach the service gallery, down the vertical access galleries.

Inside the service gallery, dedicated EMEVs that circulate in two parallel lines give access to emergency personnel and evacuate the users out of the tunnel. They are grouped in pairs, being parked at the portals of the tunnel. In such situations there will be no disturbance of the traffic flow in the non-incident traffic gallery.

Cost. The cost of the tunnel was estimated by considering a tunnel unit cost per cubic meter of excavation with a value appropriate to the tunnel layout and site characteristics. In view of these conditions, it is appropriate to adopt for this tunnel a unit cost of 420 euros per cubic meter of excavation [19, 20].

With an excavation diameter of 15.6 m, which corresponds to an area of the excavated section of 191 m^2, the unit cost of the tunnel will be about 80 million euros per kilometer. As the tunnel length is 5.1 km, the cost of the tunnel will be about 410 million euros, significantly lower than the cost of an immersed tunnel, 600 million euros, as mentioned above [19, 20].

5.3 Conclusions

The application of the TISB and TMF concepts allows to obtain a very cost-effective solution for the construction of the Algés-Trafaria tunnel crossing the Tagus River in Lisbon, with very low environmental impact, improved structural safety under earthquakes, and low construction costs (significantly lower than that of an immersed tunnel), and provides an advanced safety concept for emergency personnel access and rescue of users in the event of an accident or fire inside the tunnel.

6. Application of the TMF and TMG concepts on an optimized TBM tunnel alternative for the Fehmarnbelt Fixed Link

6.1 Introduction

The Fehmarnbelt Fixed Link is a Danish-German project, in the Baltic Sea, 18 km long, to provide a direct link by rail and road between the two countries and Scandinavia (**Figure 13**). It is part of the expansion of the Trans-European Transport Network (TEN-T) of the European Union, being co-financed by EU funds. The project will be owned and financed by Denmark and to be repaid by the users. It is being managed by Femern A/S, a Danish state-owned company.

The project aims to connect the Lolland island (in Denmark) and the Fehmarn island (in Germany), through the Fehmarn Belt. It will be for mixed traffic, with two road galleries provided with two lanes each and two rail galleries for trains at speeds up to 200 km/h, keeping the pressure variation inside the trains within acceptable limits [21].

The geological profile along the alignment of the tunnel is shown in **Figure 14** [21]. Both sides present smooth slopes near the coast areas, the deepest water being 34 m.

Figure 13.
Location of the Fehmarnbelt fixed link.

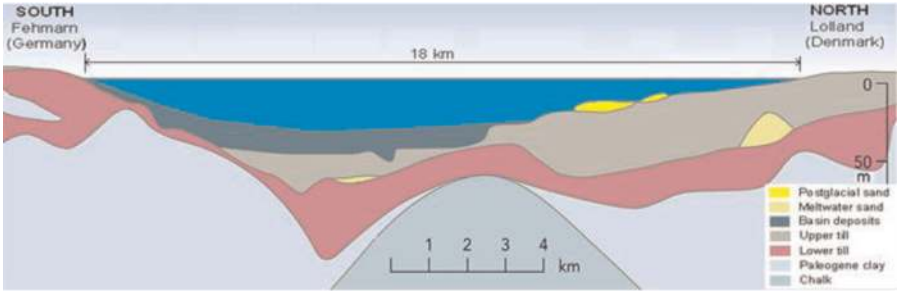


Figure 14.
Geotechnical conditions of the site.

Under the seabed the soil comprises an upper quaternary layer of post and late glacial deposits (clay and silts) followed by a Paleogene layer of highly plastic clay. The German side is characterized by Paleogene clay and some clay-till, the central basin by sand silts and clays, while the Danish side is dominated by thick deposits of clay-till.

Studies for this project began more than 20 years ago, in the 1990s. It has been studied in several variants, starting with a suspension bridge, followed by a cable-stayed bridge. As both bridge solutions received much opposition, especially from environmental organizations, an immersed tunnel solution was also further studied.

Although the costs of the cable-stayed bridge and the immersed tunnel were broadly similar, in 2011 the Danish authorities took a preliminary decision to adopt an immersed tunnel in the link. A TBM tunnel solution was also at the time studied by the promoter but, being composed of three tubes (two tubes for road traffic and another for rail traffic), despite having less environmental impact than the immersed tunnel, was rejected because the estimated cost was higher [21].

The immersed tunnel solution has then been subjected to public consultation of the Environmental Impact Assessment (EIA) by the Ministry of Transport in

Denmark in 2013. Under the framework of this consultation, the author developed an optimized TBM tunnel alternative based on the TMF and TMG concepts, which proved to be much more cost-effective than the "official" TBM tunnel solution and the immersed tunnel solution [22]. However, this alternative was not accepted, and the immersed tunnel solution obtained its approval.

The EIA of the project was also submitted to public consultation in the state of Schleswig-Holstein, in Germany, in 2014, where, after a rather harsh process, approval was also recently granted. However, the future of the project in its current form is still uncertain, as several environmental organizations threatened to challenge this decision in the German courts.

6.2 The immersed tunnel solution

The immersed tunnel solution is a conventional immersed tunnel, consisting of a single prismatic tube approximately 18 km long, 42.2 m wide, and 8.9 m high, consisting of 89 precast concrete segments in general with 217 m in length (**Figure 15**) [21]. There are also cut-and-cover sections at the ends.

The tunnel is provided with four traffic galleries: two road galleries, 11.0 m wide and 5.2 m high, and two (ballastless) rail galleries, 6.0 m wide and 6.0 m high. It also includes a service gallery, placed between the two road galleries, 2.0 m wide, for the installation of pipes and cables and to be used as temporary refugee although not allowing to be used by vehicles.

The railway galleries are provided with emergency walkways on both sides, 1.3 m wide, while the road galleries have an emergency lane on the outside but have neither internal edge nor emergency walkways.

The precast segments are placed in a trench dredged in the seabed, on a bedding layer of crushed rock. A combination of locking gravel fill and sand fill is then backfilled along the sides of the elements, while a protection layer of stones is placed across the top of the elements. Part of the dredged material is placed over the protection layer.

The execution of the works presents significant risks, since they are developed at the surface of the open sea, in a zone of intense ship traffic, and using precast segments which are significantly larger than those used in prior projects.

Environmental impact. As generally recognized, the environmental impact of the immersed tunnel solution is very significant. Among others, the large area of natural seabed of the German Natura 2000 site that will be disturbed by the construction works is worth noting, a width of over 100 m along the entire tunnel length. The huge volume of excess dredged material that will have to be placed in reclamation areas (14.8 million cubic meters) is also noted [22]. Also its significant "footprint" is impressive, with the following quantities of the most representative

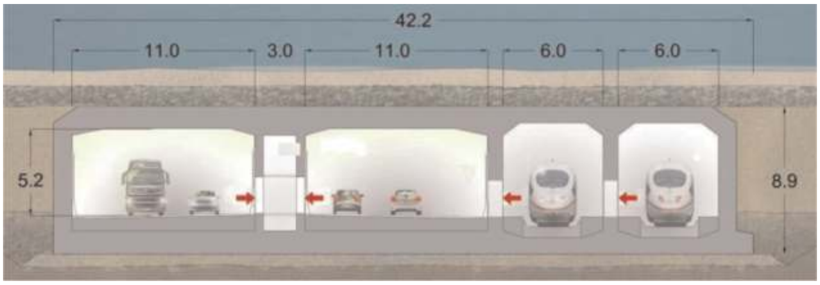


Figure 15.
Immersed tunnel solution. Current cross-section.

materials used: concrete, 3.0 million cubic meters; rock, 3.1 million cubic meters; and sand, 5.1 million cubic meters [22].

Safety in operation. In the case of fire or accident, the rescue of users relies on conventional vehicles that will use the road galleries, to which they access through escape doors, spaced 110 m [21]. However, despite this low distance between escape doors, much lower than the 500 m required by the EU rules [3, 5], as it can be shown, this does not represent a significant added value for the safety of the users of the tunnel [27].

On the contrary, the safety concept of the tunnel presents several significant shortcomings [27], namely, (a) the road galleries have no emergency walkways, so, during escape, those from behind will tend to push the others ahead into the traffic lanes; (b) with the arrival of dozens, perhaps hundreds, of people at a roadway gallery, fleeing an incident gallery, there is the risk of disruption of the traffic flow in this gallery, preventing the arrival of rescue vehicles; (c) rescue of the passengers of a train (full of 600 people) will need at least a dozen buses, which can take several hours to have them at the scene; and (d) the traffic flow in the non-incident galleries will be significantly disturbed by the occurrence of any safety problem in one of the galleries of the tunnel.

A very serious question is how to escape from the outer railway gallery. Passengers will have to cross the railway line of the internal rail gallery to reach the adjacent road gallery, which will be very dangerous and therefore should not be acceptable (see **Figure 15**) [27].

Cost. The cost of the tunnel was estimated by the owner at 5500 million euros [21], which is identical to the tenders in the meantime received for the construction. Given that the project was granted with 600 million euros of EU funds, the financial effort of the promoter will thus be around 5000 million euros, to be repaid within a 36-year period.

6.3 The optimized TBM tunnel alternative

Based on TMG and TMF concepts, an optimized TBM tunnel alternative was developed [22–27] by the author. It consists of two separate tunnels, one for road traffic and the other for rail traffic (**Figure 16**), placed beside one another at a distance of about 15–20 m, that go deep into the ground to about elevation −63 m, complemented with cut-and-cover sections at the ends.

The rail tunnel is about 20 km long and has an inner diameter of 11.5 m, with precast segments 0.45 m thick (Di/25) and 0.15 m clearance between the lining and the ground, to be injected; hence, the excavated diameter of the tunnel is 12.7 m, a common size for TBM tunnels. An intermediate slab and a central wall are then constructed, creating two parallel, independent, and isolated rail galleries with

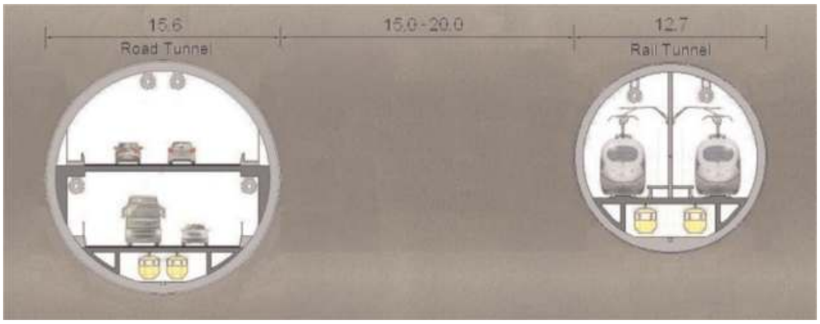


Figure 16.
Optimized TBM tunnel alternative. Current cross-section.

38 m^2 cross-sectional area, each for a direction of traffic, and a service gallery below, 2.2 m high (**Figure 17**).

The variant B of the TMG concept is used; thus, the emergency walkways of the rail galleries, 1.4 m wide (wider than those of the immersed tunnel solution), are placed on the inner side.

On both emergency walkways, there are escape doors spaced 400 m (less than the required by the EU rules [3]) that have access to vertical access galleries placed in the middle of the tunnel, at the separating wall (**Figure 17**).

Although the placement of the vertical access galleries in the middle of the tunnel causes a slight local decrease in the cross-sectional area of the railway galleries, since the vertical access galleries are outside the portal zones, the comfort conditions within the trains will not be affected.

The road tunnel is about 19 km long and has an inner diameter of 14.2 m, with precast segments 0.55 m thick (Di/25) and 0.15 m clearance between the lining and the ground to be injected; hence, the excavated diameter is 15.6 m (**Figure 18**), the same as of the largest TBM tunnels in operation, although (as referred above) larger TBM tunnels are still being built, such as the SR99 in Seattle (USA), 17.5 m in diameter, and the Tuen Mun-Chek Lap in Hong Kong (CN), 17.6 m in diameter.

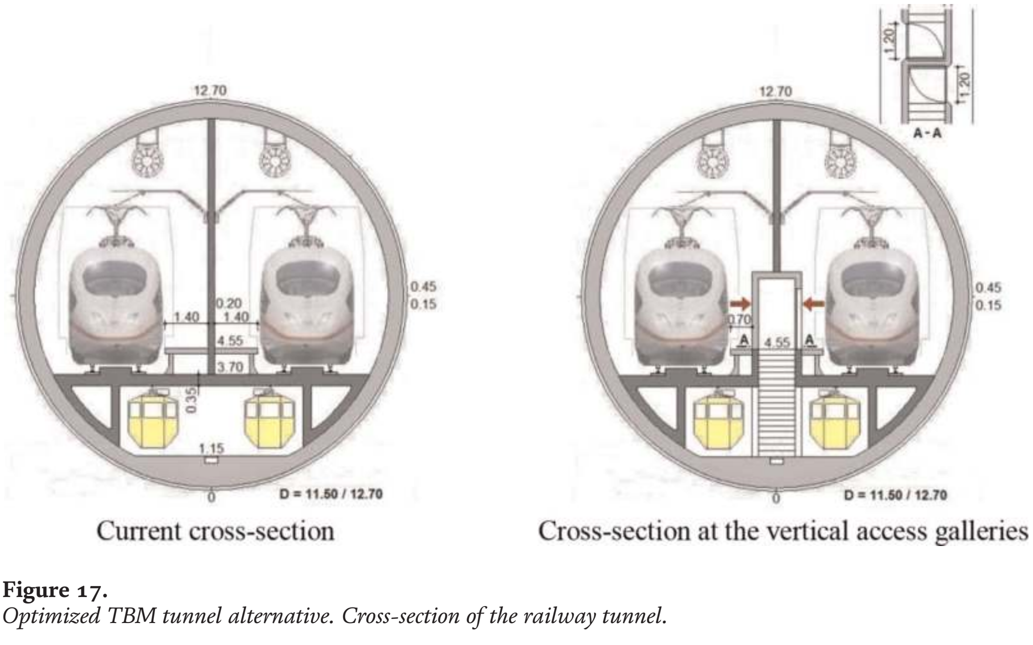
Inside the precast tunnel, two intermediate slabs are constructed, creating two superimposed road galleries, independent and isolated, each one for a direction of traffic, 5.0 m high, and a service gallery below, 2.0 m high.

Both roadway galleries have two lanes of 3.5 m wide each, external emergency lane 2.2 m wide, inner edge 1.0 m wide, and emergency walkways on both sides 1.2 m wide, over a total width of 12.6 m, greater than those of the immersed tunnel (11.0 m).

Laterally to the emergency walkways in one of the sides of the tunnel, there are escape doors spaced 400 m (less than the required by the EU rules [5]) that have access to vertical access galleries, allowing the safe passage of people between the road galleries and the service gallery (**Figure 18**).

Environmental impact. Being formed of bored tunnels, the optimized TBM tunnel alternative will not provoke any disturbance of the natural seabed along the tunnel alignment.

The volume of excavated material that will have to be placed in the reclamation areas is about 6.2 million cubic meters, much smaller than the volume of the



Current cross-section

Cross-section at the vertical access galleries

Figure 17.
Optimized TBM tunnel alternative. Cross-section of the railway tunnel.

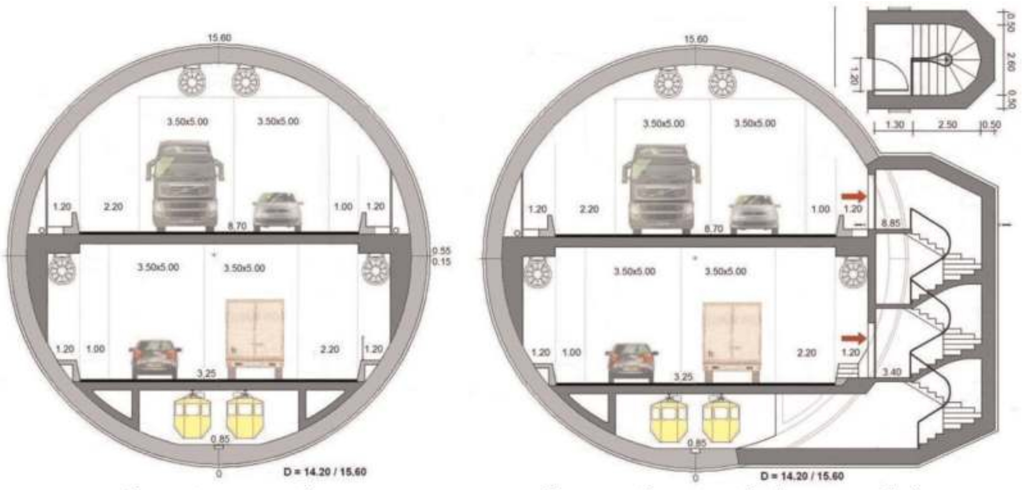
dredged material that will have to be placed in the case of the immersed tunnel solution (14.8 million cubic meters, as mentioned). The spending of natural resources in the main building materials (footprint) is as follows: concrete, 1.9 million cubic meters, and rock and sand, non-significant, which is also much smaller than in the case of the immersed tunnel solution [22–27].

Safety in operation. The TMG and TMF concepts provide to the optimized TBM tunnel alternative advanced emergency systems, which are a great step forward in the safety of traffic tunnels [22–27].

In the event of accident or fire in one of the traffic galleries of the tunnels, users will leave that gallery by walking through the respective emergency walkway to the nearest escape door, from which they achieve the service gallery of the tunnel, down the stairs of the vertical access galleries.

Inside the service gallery, dedicated emergency vehicles of the EMEV type that circulate in two parallel lines will allow for the access of emergency personnel and the evacuation of users out of the tunnel. They are grouped in “trains” (of five in the rail tunnel and two in the road tunnel), being parked at both portals of the tunnels (**Figure 19**). In such situations there will be no disturbance of the traffic flow in the non-incident gallery.

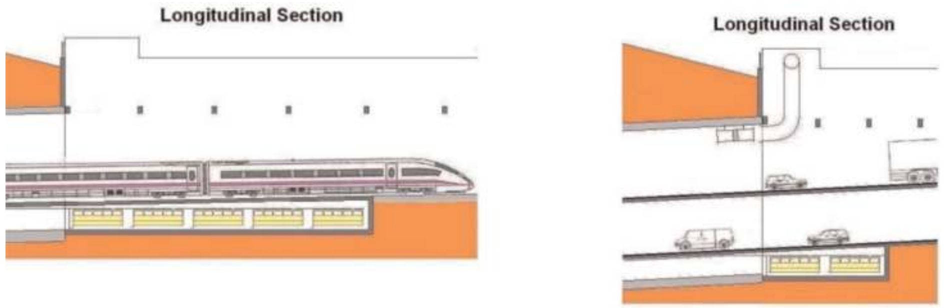
Cost. The cost of the optimized TBM tunnel alternative was estimated on the basis of the estimated cost of the “official” TBM tunnel solution, considering appropriate unit costs for each tube.



Current cross-section

Cross-section at vertical access galleries

Figure 18.
Optimized TBM tunnel alternative. Cross-section of the road tunnel.



Rail tunnel

Road tunnel

Figure 19.
Optimized TBM tunnel alternative. Portals of the tunnels.

The “official” TBM tunnel solution consists of three tubes [21]: two road tunnels with internal diameter of 14.2 m, corresponding to excavated diameters of about 15.6 m, and a rail tunnel with 15.2 m of internal diameter, corresponding to an excavated diameter of about 16.6 m, which leads to excavated volumes of about 3.82 million cubic meters for each road tunnel and 4.32 million cubic meters for the rail tunnel.

Whereas the estimated cost of this solution was 6800 million euros, and considering that the unit cost of the rail tunnels is about 70% the unit costs of the road tunnels [25–27], unit costs of 450 euros per cubic meter for the rail tunnel and 635 euros per cubic meter for the road tunnel are obtained.

Hence, for the optimized TBM tunnel alternative, unit costs of 450 euros per cubic meter for the rail tunnel (the same as the one obtained for the “official” TBM tunnel solution) and 650 euros per cubic meter for the road tunnel (slightly higher than the one obtained for the “official” TBM tunnel solution, since there are the vertical access galleries to build) are assumed.

Whereas in this case, the excavated volumes are about 2.54 million cubic meters for the rail tunnel and 3.63 million cubic meters for the road tunnel, the estimated costs will be 1150 and 2400 million euros for the rail and the road tunnel, respectively. Therefore, the estimated cost of the TBM tunnel alternative is 3550 million euros, which is less than 2/3 the cost of the immersed tunnel solution [25–27].

It should also be noted that the unit costs obtained for the “official” TBM tunnel solution are significantly higher than those normally obtained in tunnels under similar conditions, so it has to be admitted that the estimated cost is exaggerated by at least 15%.

Thus, the cost of the optimized TBM tunnel alternative will probably be around 3100 million euros [27], so the financial effort of the promoter would be about half of that of the immersed tunnel solution.

6.4 Conclusions

Given the above considerations, the following main conclusions are drawn.

With regard to the environmental impact, while in the immersed tunnel proposal it is very significant, in the Optimized TBM tunnel alternative, it is very low; in particular it avoids any disturbance of the natural seabed along the tunnel.

Regarding the safety in operation, while the immersed tunnel solution has several weaknesses in its safety concept, the optimized TBM tunnel alternative presents an advanced safety concept, in which the rescue of users relies on dedicated unmanned electric vehicles operating inside a service gallery, so completely independent of the access conditions inside the traffic galleries.

With regard to costs, the cost of the optimized TBM tunnel alternative is about 3100–3550 million euros, which is less than 2/3 the cost of the immersed tunnel solution, and the financial effort of the promoter would be halved, allowing for an equivalent reduction in the tolls to be paid by the users or in the repayment period.

In summary, the optimized TBM tunnel alternative is undoubtedly much more cost-effective than the immersed tunnel solution.

7. Final remarks

The TISB, TMG, and TMF concepts are innovative developments that represent a step forward in the construction of rail and road tunnels executed with the TBM technique.

In addition to the intrinsic environmental advantages of TBM tunnels, they provide improved seismic behavior, reduction in the construction costs, and improvement of safety during operation.

Regarding the seismic behavior of the TBM tunnels built on soft ground, the TISB concept provides the tunnels with the necessary strength and ductility, avoiding the need for additional soil treatments.

Furthermore, although being formed by single tubes, each tunnel accommodates two completely independent and isolated galleries of traffic (for rail or road) and a service gallery below, which allows a very reliable safety concept, much more reliable than any currently existing.

With regard to costs, simply comparing the excavated volumes of the referred single-tube tunnels with those of the equivalent conventional solutions using two parallel tubes connected by cross-passages shows that reductions of more than 20% will be easily achieved.

With regard to safety in operation, the service gallery at the base of the tunnel provides a very reliable pathway for access of the emergency personnel and the rescue of users in the event of accident or fire inside the tunnel, through dedicated emergency vehicles (EMEVs), therefore independent of the availability of conventional rescue vehicles or the access conditions inside the traffic galleries of the tunnel.

In summary, the TISB, TMG, and TMF concepts provide very cost-effective and safe solutions that can be of great value in the construction of the rail and road tunnels of tomorrow, especially long tunnels.

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