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Seven Tunnels to the Greater Vitória and their Geotechnical Aspects

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ABSTRACT: Vitória, is the Espírito Santo (ES) state capital, an island densely populated, important considering its harbor areas, with an intensive vibrant economy leading to a much greater GDP than the national average. Vitória has been demanding new road connections with its neighbor cities: Vila Velha and Cariacica, both part of the conurbation of its grater urban area, as well some arterial systems has their own demands to enhance quality of traffic and allow time savings on transit trips. In this paper presents 7 tunnels for the Greater Vitória. Two immersed solutions for the Vitória Bay. As an alternative proposal for the Vitória and Cariacica link under the Vitória Bay channel it's presented an immersed tunnel solution. An immersed tunnel proposal between Vitória and Vila Velha and the geotechnical aspects of these two immersed solutions are pictured in details. Another set of needed tunnels are presented. Many factors indicate that the tunnels described to enhance the arterial systems of the road nework of Vitória are best solutions. The cost of the construction of each solution are assessed with respect the international and the local costs of each one.

KEYWORDS: Tunnel, Vitória, immersed tunnel, NATM

RESUMO: Vitória, capital do estado do Espírito Santo (ES), é uma ilha densamente povoada e economicamente importante, com um PIB muito superior à média nacional, graças em parte à sua área portuária. A cidade demanda novas ligações rodoviárias com seus vizinhos Vila Velha e Cariacica, ambos integrantes da região metropolitana. Além disso, o sistema arterial existente enfrenta gargalos que prejudicam a qualidade do tráfego e aumentam o tempo de viagem. Este artigo apresenta um estudo sobre a implementação de sete túneis na Grande Vitória. Duas soluções envolvem túneis submersos na Baía de Vitória. Como proposta alternativa para a ligação entre Vitória e Cariacica sob o canal da baía, apresenta-se um túnel imerso. O artigo detalha a proposta de um túnel imerso entre Vitória e Vila Velha, incluindo os aspectos geotécnicos de ambas as soluções submersas. O estudo também analisa a necessidade de outros túneis para a região. Diversos fatores indicam que os túneis propostos para melhorar o sistema arterial da malha viária de Vitória representam a melhor solução. O custo de construção de cada opção é avaliado considerando referências nacionais e internacionais.

KEYWORDS: Túnel, Vitória, túnel imerso, NATM

1 INTRODUCTION

Vitória's island location restricts its road network, as shown in Prandina's illustration of the coastal contours (Figure 1). This limitation is further compounded by a steep central rock massif occupying roughly 32% of the central-western area, hindering the development of through roads.

Despite its size (approximately 13 km in diameter), Vitória, the capital of Espírito Santo with a population of 355,000, serves as the economic hub of the Greater Vitória Area (GVA). The GVA encompasses six surrounding municipalities (see Figure 1): Vila Velha, Cariacica, Serra, Viana, Guarapari, and Fundão, with a combined population of 1.5 million. Notably, a staggering 227,000 people commute daily to and from Vitória via its limited road connections (IBGE, 2015).

Alone, Espírito Santo (ES) exports more than 60% of the iron ore, more than 75% of the dimension (ornamental) stone for finishings exported of the country, and it has become the second in petroleum

production, with an average of 170.000 barrels per day (Petrobras, 2015). In 2023, the industrial sector advanced by 9.1%, marking the best performance for the category since 2011, when the increase had been 12.3%, according to the GDP released by the Brazilian Institute of Geography and Statistics (IBGE, 2024).

Figure 1. Two pictures of the 1st and the 2nd bridges linking Vitória and Vila Velha (apud Vitória Port authority, 2016).

Vitória's booming economy, exceeding the national average GDP, necessitates improved transportation links with neighboring cities. Vila Velha and Cariacica, part of the Greater Vitória conurbation, require better connections to Vitória to reduce traffic congestion and travel times. This paper proposes seven tunnels as potential solutions.

Two immersed tunnel options are explored, with detailed analyses of the geotechnical conditions in Vitória Bay. For the proposed "fourth connection" between Vitória and Cariacica, the local government presented a conceptual bridge design with a width of 36 meters and a length of 1.4 kilometers. This paper offers an alternative immersed tunnel solution for this specific route.

Neither Espírito Santo nor Vitória has extensive experience with tunnel construction for road infrastructure. However, Kneib & Prandina (2004) previously proposed an immersed tunnel between Vitória and Vila Velha, with detailed geotechnical assessments. Prandina (2014) also presented the Cristovão Jaques tunnel, utilizing the cut-and-cover method to connect Reta da Penha Avenue to the Castelo Branco Bridge.

On the western side of Vitória Island, along Serafim Derenzi Avenue, two additional tunnels through a rock massif are proposed to reduce travel distances and improve road safety.

A sixth major solution, a NATM tunnel, is presented to cut through the central massif of Vitória Island. This option shares similar geotechnical challenges with the previous two rock massif tunnels. Finally, the seventh tunnel would connect two sections of Cesar Hilar Avenue.

This paper argues that these proposed tunnels represent the optimal solutions for enhancing the arterial road network within Greater Vitória. A cost analysis, comparing both international and local construction costs, is presented for each solution.

2 ROAD CONNECTIONS AND ECONOMIC DEVELOPMENT

Vitória Island sits 150 to 1,500 meters off the mainland, with shorter distances on the northeast side and longer ones on the southwest. Three existing bridges connect Vitória to the city of Vila Velha in the south:

i) First Bridge (Florentino Avidos);
ii) Second Bridge (connects Vitória, Vila Velha, and Cariacica)
iii) Third Bridge (Darcy Castello de Mendonça)

The northern part of the island has three additional bridges to the mainland, but they are shorter and serve local traffic only, not functioning as major arterial routes.

Figure 2 visually supports the notion that transportation infrastructure, like roads, can stimulate economic development. The image on the left side shows a clear correlation between denser road networks

and higher employment levels in the surrounding areas. This suggests that a lack of proper infrastructure can hinder balanced economic growth across a region.

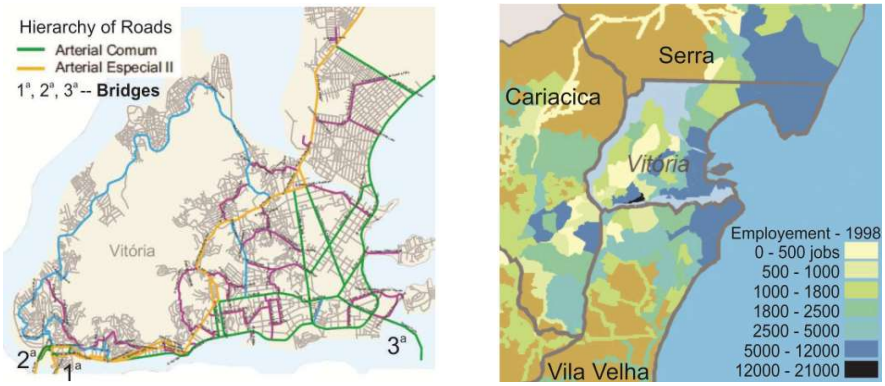

Figure 2. The arterial system of the road network of Vitória and the Jobs per zone – Greater Vitória and (PDTU, 1998)

2.1 Saturated Arterial System and Public Perception

Traffic congestion in Vitória is a major concern, causing longer travel times during peak hours. Research by Kneib (2011) suggests that overloaded road systems significantly reduce quality of life in urban areas. Vitória experiences this problem daily, with traffic jams plaguing all access points.

Studies by DaMatta (2008) conducted over a decade ago already highlighted the negative impacts of traffic congestion in Vitória, including stress, fatigue, and safety risks for drivers and pedestrians. This was confirmed by camera observations that documented frequent conflicts between drivers and pedestrians.

The current situation is concerning. Traffic jam data from 2016 shows congestion across 60 kilometers of roads, and average speeds on Reta da Penha Avenue during peak hours have plummeted from 8 km/h in 2008 to a mere 4 km/h along the entire 7.5 km stretch (Marcondes, 2018).

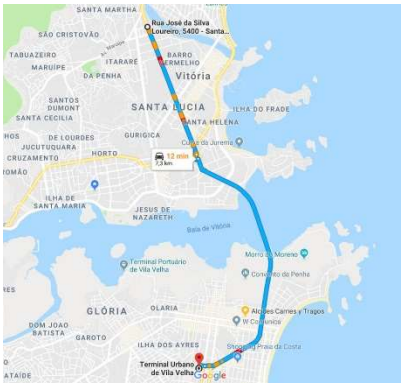

Figure 3. Road stretch including Reta da Penha with average speed of 4 km/h (Marcondes, 2018).

The existing bridges themselves have greater flow capacity than Vitória's road system. However, since users cannot access them twice a day, the immediate assumption is that a new bridge or connection would improve traffic flow.

Another study highlighting the negative impact of traffic conditions in Vitória comes from Caus and Santos (2008). They describe a chaotic scenario of traffic conditions resulting in increased pollution and a decline in quality of life. In 2008, public perception of traffic quality was notably low. Over the subsequent five years, the total number of vehicles in the state increased by over 50%, with a peak growth of 13% in 2009.

3 FEASIBLE TUNNEL PROJECTS WITH REAL-WORLD POTENTIAL

Disclose tunnel solutions was conceived as the optimal approach to provide the society with all available connection options. This was necessary as the technical community had previously harbored negative prejudices against tunnel solutions. Recognizing the significance of tunnels for Vitória's efficient infrastructure, they serve as a valuable tool in addressing the ongoing challenge of traffic congestion.

3.1 The Fourth Link of Vitória and Vila Velha

Vitória and Vila Velha are currently connected by three bridges, each with unique considerations for maritime traffic. The Fourth Link project proposes a novel solution: an immersed tunnel approximately 800 meters long. This tunnel will utilize the existing João Santos (red line) and Paulino Muller (blue line) avenues for access.

Figure 4. The Fourth Link of Vitória and Vila Velha (modified Kneib & Prandina, 2004).

The immersed tunnel's cross-section (as depicted in Figure 5) will feature dedicated lanes for both regular vehicles and Bus Rapid Transit (BRT). Additionally, a central chamber will be incorporated to accommodate a Light Rail Transit (LRT) or Metro line. This central chamber serves a dual purpose: it provides an alternative escape route in case of emergencies within the tunnel and enhances overall safety. The tunnel ramps will have a maximum incline of 3%, adhering to the minimum recommended grade by the Federal Highway Administration (FHWA, 2004).
Geologically, Vitória Bay, where the tunnel will be built, consists of sedimentary layers of soft clay and marine clay. This type of terrain is well-suited for immersed tunnel construction, making it a familiar and manageable project for experienced international companies.

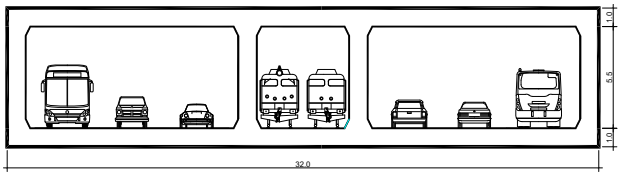

Figure 5. Conceptual cross section of the Fourth Link (modified Kneib & Prandina, 2004).

A map based on Larsonneur's classification system (Dias, 1996) reveals a more uniform distribution of sediments in Vitória Bay. The predominant texture is muddy terrigenous, with a notable exception. A band of marls (referred to as carbonate muds by Dias, 1996) stretches from Ilha das Caieiras to near Santo Antônio, positioned along the bay's central region close to the main channel (Fig. 5).

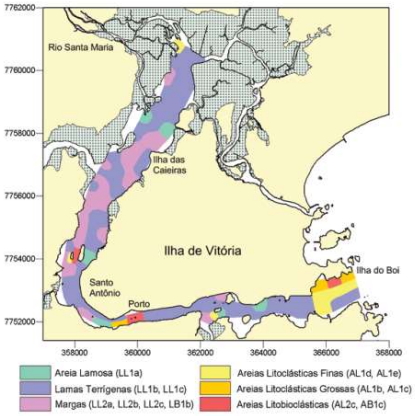

Figure 6. Map of textural classification of sediments in the Bay of Vitória, according to the modified classification by Larsonneur (Dias, 1996)

The construction cost of immersed tunnels can vary considerably due to several factors. These include tunnel length, soil conditions, depth of immersion, environmental concerns, labor costs, and engineering complexity. Immersed tunnels are typically one of the more expensive tunneling options. This is due to their construction method, which involves prefabricating tunnel segments in a dry dock, floating them into place, and submerging them in a pre-dredged trench.

Currently, the international construction cost for immersed tunnels in shallow seas, excluding land acquisition, is estimated at around €255 million per kilometer. This is based on a similar project under construction: a 1.7 km immersed tunnel accommodating both road and rail traffic. This project features two double-track tubes for vehicles and two single-track tubes for trains. Expected for completion alongside the opening of the Fehmarn Belt fixed link, the total construction cost for the tunnel, including both road and rail components, is €714 million. The project is expected to be operational by 2028, coinciding with the completion of the Danish tunnel.

3.2 The Vitória-Cariacica Tunnel Project

A new immersed tunnel connection between Vitória and Cariacica leverages existing routes proposed by DER-ES (2014). This design minimizes environmental impact by utilizing a shorter immersed tunnel segment (533 meters) for the underwater crossing, compared to a longer bridge spanning the seabed and residential areas. The total onshore distance between the two cities remains relatively short at just 373 meters.

Immersed tunnels are a proven solution worldwide (see Figure 12) for short underwater crossings in densely populated areas, especially when maritime traffic is a concern. This project proposes an immersed tunnel with three main sections:

- East Tunnel/Approach (Vitória): This section features two lanes on each side and seamlessly integrates with existing roads. Details on its cross-section and dimensions (in meters) can be found in Figure 7.
- West Tunnel/Approach (Vitória): Details on this section are not provided here, but presumably it mirrors the eastern approach.
- Subaquatic Crossing (Vitória to Cariacica): This 533-meter immersed tunnel section forms the core of the new connection.

An additional dedicated cycle lane will be built on the east side of Dario Lourenço de Souza Avenue, allowing cyclists to access Cariacica through the tunnel.

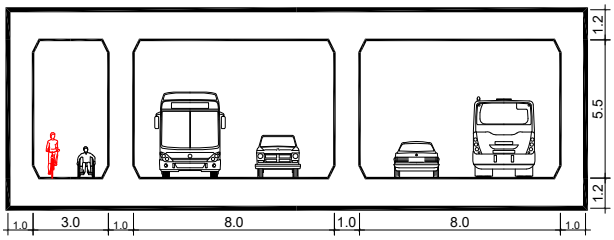

Figure 7. Cross section of the East tunnel in Vitória.

Mirroring the 4th Bridge design, the western approach on Dario Lourenço de Souza Avenue will cater to both BRT users with a dedicated lane and individual vehicle traffic with two additional lanes. This design allows cyclists from Vitória to conveniently access Cariacica through the immersed tunnel. Similar to the eastern approach, the western side seamlessly integrates with existing roads and features two lanes for each direction of travel. For a detailed view of the western tunnel's cross-section with dimensions in meters, please refer to Figure 8.

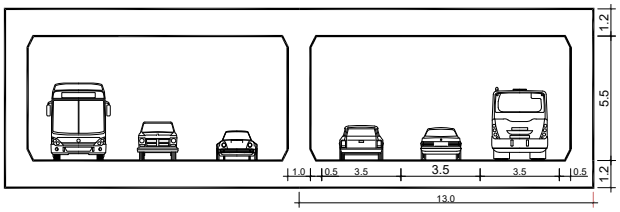

Figure 8. Cross section of the West tunnel in Vitória.

The East tunnel on the Vitória side commences with a cut-and-cover approach, as depicted in Figure 9.

Figure 9. Vitória-Cariacica Link adopting 2 different gradients: 3% on the tunnel lining and 6% on the approaches (apud Prandina, 2016).

Figure 10 illustrates the elevation profile of the eastern tunnel approaching Cariacica. The tunnel itself will have an elevation of 3 meters, while the approaches will have a 6% incline. This translates to a total road width of 833.71 meters for vehicles traveling across Vitória Bay Complex (VBC).

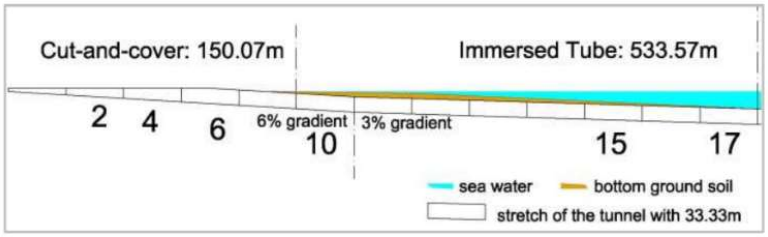

Figure 10. Vitória-Cariacica Link adopting a constant gradient of 3% on the approaches and tunnel lining (apud Prandina, 2016)

Replacing the proposed 4th Bridge with an immersed tunnel offers several advantages, both objective and subjective. Table 1 compares these two engineering solutions across various aspects. While some criteria may be subjective, the evaluation is straightforward.

The geotechnical conditions along the proposed tunnel route are similar to those assessed for the DER-ES (2014) bridge project. In fact, the same geotechnical data from 18 boreholes (identified as SP - Standard Penetration Test) conducted for the bridge design will be used for the immersed tunnel.

Additionally, the basic summary of geotechnical information for the alignments 4 and 5 profiles is illustrated in Figure 11.

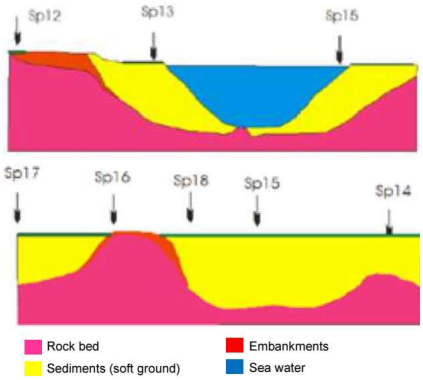

Figure 11. Profile of the boreholes in different alignment (apud Prandina, 2016)

The cost of construction of this immersed tunnel projects, which reachs 900 meters of length, excluding land expropriation, on shallow sea areas can be estimated in 315 million euros.

3.3 The Cauê Tunnel Project

Prandina (2010a) proposed a design sketch (see Fig. 12) for the Cauê Tunnel, illustrating dedicated lanes for both Bus Rapid Transit (BRT) and cars. This tunnel, located beneath Cauê Square, would directly connect to the 3rd Bridge on Reta da Penha. This aims to solve the traffic congestion caused by three intersections where a high-volume arterial road merges into a slower local road network. Geologically, the area consists of soft layers of marine clay and sand resting on a bedrock foundation, typically granite.

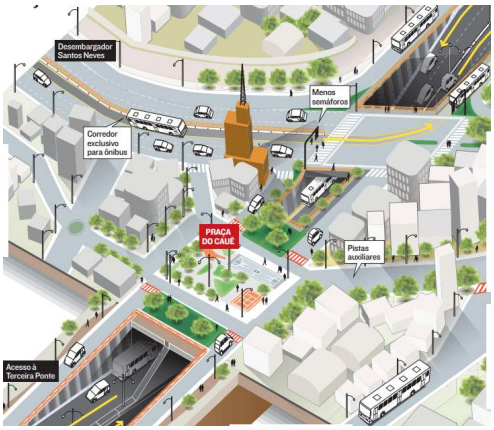

Figure 12. Profile of the boreholes in different alignment (modified Prandina, 2014)

The chosen construction method, cut-and-cover, utilizes struts for support, offering a more cost-effective alternative to tiebacks. However, this method requires the temporary demolition of Cauê Square to facilitate the construction of a 400-meter long tunnel with a 22-meter span and 8-meter depth. Following construction, the square will be fully reconstructed.

The type of work is quite simple, using reinforced concrete piles and slabs. The earthworks amount to 70,000 m^3, and the cost, typically expected at 60 million dollars per kilometer, brings the construction cost to 24 million dollars.

Table 1. Summary of the 7 tunnel projects proposed in this paper and their costs

Tunnel		Construction Method	Length (meters)	Geology	Cost (U$ million)
1	Vutória Vila Velha	Immersed tube	800	Sedimentary deposit	255,0
2	Vitória Cariacica	Immersed tube	900	Sedimentary deposit	315,0
3	Cauê Plaza Tunnel	Cut-and-cover	400	Sedimentary deposit	24,0
4	Conventional Tunnel (Central Massif)	NATM	2000	Rock	55,0
5	Cesar Hilal Av. Tunnel	NATM	600	Rock	16,5
6	NATM Tunnel - I (Serafin Derenzi)	NATM	350	Rock	9,6
7	NATM Tunnel – 2 (Serafin Derenzi)	NATM	600	Rock	16,5

3.4 The other 4 tunnels to Improve the quality of the road network

To achieve the seven tunnels to improve the traffic quality in the Greater Vitória, the following tunnels may be listed: i) The Immersed Tunnel connecting Vitória and Vila Velha (approximately 800 m); ii) A conventional Tunnel through the central massif of the island (2 km); iii) Cesar Hilal Av. Tunnel (600 m); iv) Two conventional tunnels in Serafin Derenzi, also in rock (500 m and 700 m each); v) Cauê Plaza tunnel to connect the 3rd bridge with its arterial system beneath a residential area (400 m).

4 CONCLUSION

This paper examined the potential tunnel projects in Greater Vitória aimed at enhancing its traffic quality, which has been strained by the absence of new links between its major cities. The construction of the seven tunnels could be carried out using well-established methods, requiring a total investment of approximately 692 million dollars. For two of the more costly projects, the toll solution may be considered to secure funding for both construction and operation.

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