Investigation, Design and Construction of 5 NATM highway tunnels – Serra do Mar, Brazil

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ABSTRACT: The Serra do Mar mountain range is one of the most remarkable geological and geomorphological features of Brazil's southeastern coast, with more than 1.500 km length. In the northern coast of São Paulo State, between the cities of São Sebastião and Caraguatatuba, the Serra do Mar encompass altitudes varying from a few meters to 1.000 m above sea level, in just a few kilometers of horizontal distance, resulting in a very steep relief. The mountain range is a very dynamic and challenging environment for any infrastructure project, with a very heterogeneous soil thickness and frequent soil/rock movements. In this context, 5 NATM tunnels were designed and excavated. Each tunnel is a twin-bore, two lanes vehicular tunnel, resulting in more than 13 km of excavation, with a 100 m² cross section. The tunnels cross 3 different lithologies in different degrees of weathering, ranging from residual soil to unweathered rock.

1 INTRODUCTION

This work is mainly a descriptive paper with a vision more directed towards geological aspects, with the goal of spread and discuss geological and geotechnical features of a challenging region.

1.1 *The Tamoios transport corridor*

The Nova Tamoios Contornos Highway is part of a transport corridor connecting two main highways (President Dutra Highway, BR-116/SP-060 and Governador Carvalho Pinto Highway, SP-070) to the São Sebastião Port. The SP-060 and SP-070 highways connect São Paulo and Rio de Janeiro (the two largest Brazilian state capitals. Connecting these two major highways is the Tamoios Highway (SP-098), an 82 km long highway that begins in the São José dos Campos city region and ends in Caraguatatuba city, on the shore. Currently, the connection between the coast area and SP-060/SP-070 highways is made by a decades old sector of the Tamoios highway crossing the Serra do Mar, and by the SP-055, a two lane/single lane highway that runs inside Caraguatatuba and São Sebastião cities.

The Tamoios Highway is composed of 3 sectors: Plateau sector, Mountain Range sector and the Contornos sector (Nova Tamoios Contornos, in which the tunnels described here are inserted). Both the Plateau and the Contornos sector are under construction, and these sectors will replace the current roads as the main paths for tourism and the São Sebastião Port.

1.2 *Contornos Highway and the Serra do Mar mountain range*

The Nova Tamoios Contornos is a 36 km highway that runs across flat, sedimentary plains, and steep hillsides of the Serra do Mar mountain range, composed of crystalline rocks. This resulted in a wide range of geological and geotechnical issues during design and construction phase. From embankment foundations on soft soil, to many types of slope supports on soil and rock slopes on the hillsides of the Serra do Mar

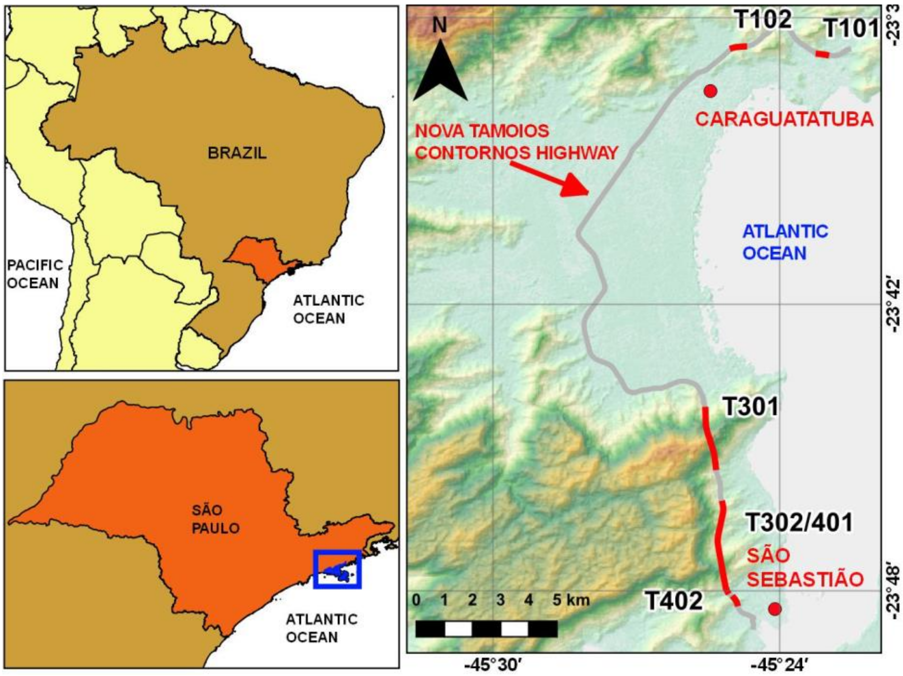

Figure 1. Nova Tamoios Contornos location.

Other major features of this project included design solutions to deal with debris flow susceptibility, talus deposits, rockfall possibilities and mass movements, some of them close to urban areas.

Figure 2. An example of a sector of the Tamoios Highway under construction. It is possible to see the Serra do Mar steep hillsides and São Sebastião urban area.

The Serra do Mar mountain range is an important geological and geomorphological feature of Brazil's southeastern coast, with more than 1.500 km length. In the northern coast of São Paulo State, between the cities of São Sebastião and Caraguatatuba, the Serra do Mar encompass altitudes varying from a few meters to 1.000 m above sea level, in just a few kilometers of horizontal distance, resulting in a very steep relief. In terms of rainfall, the region has a 2.500 mm annual mean accumulated amount. This results in a very dynamic and challenging environment for any infrastructure project, with a very heterogeneous soil thickness and frequent soil/rock movements (like landslides and debris flows).

In this context, 5 NATM tunnels for the Nova Tamoios Contornos Highway were designed and excavated. Each tunnel is a twin-bore, two lanes vehicular tunnel, resulting in more than 13 km of excavation, with a 100 m² cross section. The tunnels cross 3 different lithologies: granite, migmatite and gneiss, in different degrees of weathering, ranging from residual soil to unweathered (fresh) rock. Also, mafic dykes and sills are common in the region.

1.3 *Geology*

The study area is located in the central Mantiqueira Province, composed mainly of gneissic-migmatitic rocks and granitic bodies that fit the geostructural Gneissic-Migmatitic Complex. The foliation presents a ENE-WSW direction concordant to the general structure of the Brazilian southeastern platform where large shear zone systems predominates. The rock mass is in general non-weathered with few weathered portions mostly associated to fractures. The geological map below is based on Dias Neto *et al*. (2009), Suguio (1978), and Suguio & Martin (1978)

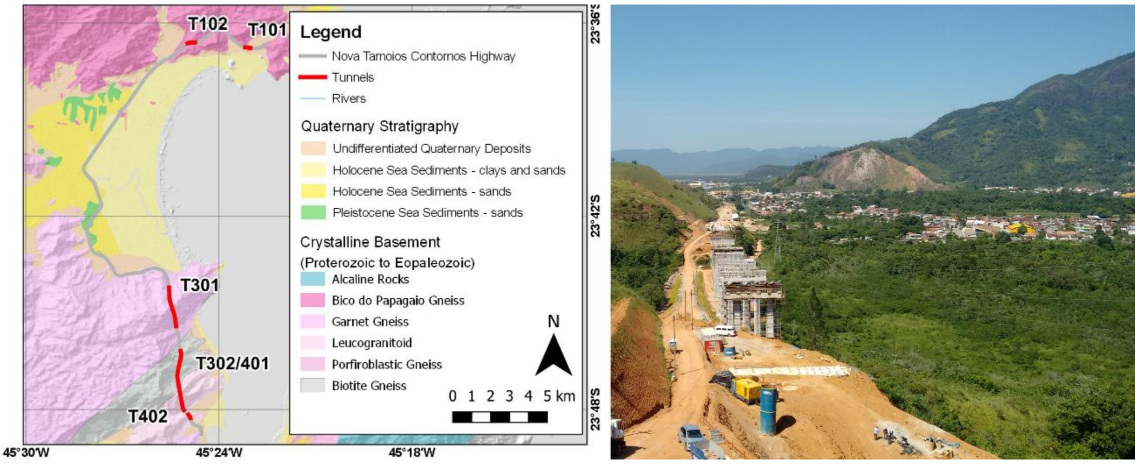

Figure 3. Nova Tamoios Contornos geological map and an example of the region's geomorphology: the Serra do Mar hillsides at the right, and the sedimentary plains at the background. Picture from the T102 South and the Contornos highway under construction

1.4 *Tunnels*

As described before, each tunnel is actually a twin-bore tunnel, and each one is named as Right or Left track. Data for tunnels length and maximum overburden is provided in Table 1, below.

Table 1. Tunnels length and overburden.

Tunnel	Track	Tunnel Length (m)	Maximum Overburden (m)
T101	Right	294	60
	Left	295	56
T102	Right	407	62
	Left	384	58
T301	Right	2.267	447
	Left	2.266	437
T302/401	Right	3.440	352
	Left	3.452	352
T402	Right	228	56
	Left	240	48

All of Contornos tunnels portals were designed and excavated in residual soil or weathered rock, due to the always present residual soil layers in the region, with at least some meters of thickness.

T101, T102 and T402 cross small and relatively isolated hills, with peak overburden close to the mid-point of the tunnel, and smooth uphill/downhill relief at both ends. T101 is located at a mostly weathered granite mass, with rock occurrences in the middle of the tunnel. T102 is also located at a granite dominated region, but with a large, more than 40 meter thick mafic dyke in the middle of the tunnel. T402 is at a biotite gneiss area, with sections with only soil or weathered rock occurrences, and others with unweathered rock. Also, mafic dykes were present.

T301 runs across a tall and large Serra do Mar crest, that reaches an altitude of 600 meters above sea level. This high overburden acts as an advantage to the rock quality, because there are no topographic low points along the tunnel. Also, there is a lithological contact zone about halfway of the tunnel, between migmatites and biotite gneiss. The northern portal presented rock boulders scattered over the residual soil in the terrain, that required careful removal from the constructor.

T302/401 is the longest tunnel, but do not present the highest overburden. Nor is the topographic profile over the tunnel a regular one, it is actually irregular and with low points, making the overburden vary from almost 100 meters to values like 20 meters in a place far from the portals. This situation presented challenges to the excavation, since the rockmass was heterogeneous and a high density of fractures and joints was often found.

A feature that is worth to notice is that the Contornos tunnels do not cross the Serra do Mar in a perpendicular way to the mountain range axis, but rather, run along it’s hillsides and steep slopes. This results in very different overburdens for 2 tracks of the same tunnel, because one track is always more to the inside of the rockmass than the other, often resulting in different design approaches.

2 METHODOLOGY AND TUNNEL DESIGN

2.1 *Preliminary Design Changes*

The preliminary design had foreseen single bore tunnels only, with a larger cross section, and lanes in both ways inside the same tunnel. Due to tunnel fire safety needs and measures, placed by govern authorities when analyzing the project, it was decided to change the design premise to twin bore tunnels. This change was made in part because of the works and costs needed to excavate a larger cross section, combined with the measures to assure fire safety, like the transverse ventilation system needed.

Other main changes that occurred from the Preliminary Design phase to the Detailed Design phase were the changes in alignment and length of T301 and T302/401 tunnels. The previous alignments were shorter, resulting in more sectors of earthworks and the need of more construction paths along the slopes and hillsides of Serra do Mar. This led to more sectors exposed to mass movements vulnerability. The Detailed Design phase improved this situation by increasing the tunnels lengths and placing the portals in more accessible places, avoiding hillside sectors and also resulting in less vegetal suppression.

2.2 *Field investigations and laboratory tests*

Investigation for the tunnels began with the usual map and bibliographic research, stereoscopic photo interpretation for major discontinuities identification and surface geological mapping. The investigation continued with percussion and rotary drilling, Lugeon test, geophysical field surveys and uniaxial compressive strength (UCS) tests.

Geophysical surveys included electrical resistivity imaging, magnetic and seismic diffraction methods. The geophysical survey lines ranged from lines parallel to the tunnel alignment along the entire tunnel length, to lines perpendicular to the tunnel alignment, close to the tunnel portal, so that geophysical cross sections could be made, making it possible to visualize both tracks (tunnels).

Some investigation activities (like surface mapping and drilling) were not one-shot attempts, but rather, happened in an iterative process, influencing and being influenced by changes in design, like geometry modifications and tunnel portal allocation. This required a high level of interaction between the tunneling and geological-geotechnical team and other design teams, like geometry. It also required several and frequent field visits on a time span of more than a year, to identify and describe the maximum number of features possible, due to frequent design adjustments.

2.3 *RMR*

Bieniawski (1989) Rock Mass Rating (RMR) was used to divide the drilling samples into rock mass classes, so that the information could be summarized in a geological section for each tunnel, including all the investigation data. Caution was taken when classifying the drilling samples, to best achieve a balance between not penalizing large portions of sample because of small poor sectors and, at the same time, identifying when a bad sector of sample was actually a feature that could present an issue to excavation.

2.4 *Design documents*

The RMR values, together with the geological information described in the previous sessions was then presented and discussed with the tunneling team, to find the best way of using all the information provided in the geotechnical design. Again, this was not an only one time interaction, but a constant and continuous process, including field visits with geotechnical engineers from the tunneling team.

The result was the geological and geomechanical tunnel section, summarized in the form of design drawings. These drawings included, besides the geological section with RMR classes, the excavation and support classes (based on the RMR classes), multiple drift method (if necessary), excavation sequence, lining type, support and water treatments.

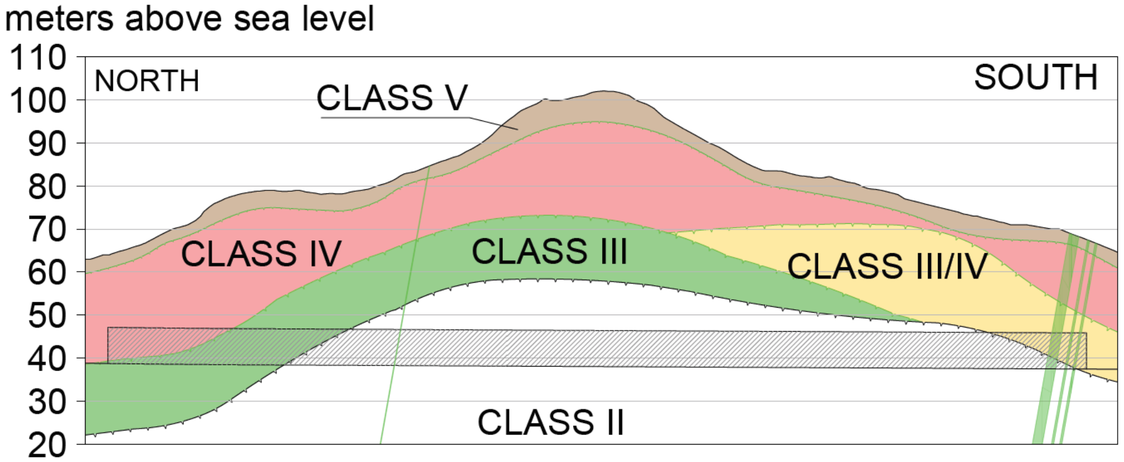

Figure 4. Simplified version of T402 geological and geomechanical cross section from a design drawing. Greem diagonal lines are mafic dykes. “Class II” to “Class V” are RMR classes.

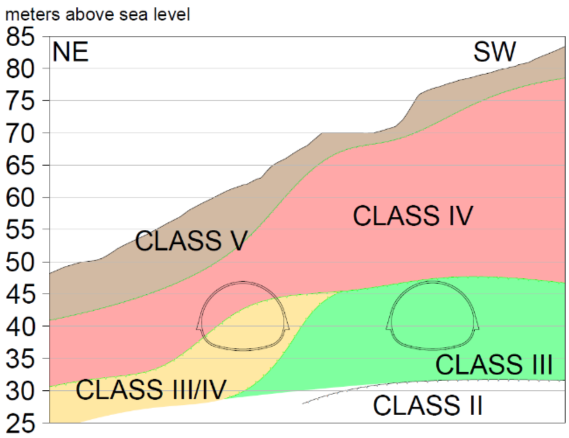

Figure 5. Simplified version of T402 geological and geomechanical cross section perpendicular to the tunnel alignment, from a design drawing. “Class II” to “Class V” are RMR classes.

The geological team also elaborated geological cross section drawings perpendicular to the tunnel alignment axis, showing RMR classes varying from one track to another of the tunnels. This is was necessary because of the feature discussed before, that the Contornos tunnels do not cross the Serra do Mar in a perpendicular way to the mountain range axis, but rather, run along it's hillsides and steep slopes. It was an issue foreseen in the design phase, that proved to be an issue in excavation phase, requiring different support measures for each track of the tunnels during many times.

3 DESIGN CHANGES

During investigation and design phase some tunnels undergone significant design changes: T101 northern portal had a massive change in portal slope treatment approach, due to past erosions and not legal soil exploration in the same site; T301 northern portal had an early design reallocation, due to talus deposits in the former position; T401 and T302 had nearby portals in an area of high possibility for landslide and debris flow occurrences, so the portals (along with one high cut, one embankment and one bridge) were eliminated, resulting in one tunnel.

3.1 *T101*

T101 northern portal is located in an area that have been used, for decades, for illegal soil exploration. The exploration had been inactive for many years before the Contornos projected started, and this resulted in many erosion occurrences in the slope around the portal, to the point that a large erosion scar had formed, and the slope was in a constant erosion prone state.

The initial design versions for the portal did not predicted geotechnical measures for all the slope, only in a small area around the portal. With participation of geology and geotechnics consultants, an agreement was reached, together with the client, that if the slope was not incorporated in the portal design, it could present future problems to the slope stability. The final design version dealt with an area much larger than the portal needed, but the slope was stabilized and an urban problem was finally solved, after decades of land misuse.

Figure 6. T101 northern portal before (left) and after (right) construction and erosion control measures.

3.2 *T301*

T301 had, in the initial portions of the geometry design, its northern portal placed on a talus deposit, on the foothill of a Serra do Mar crest. These types of deposits in the Serra do Mar region in general are composed of large rock boulders (sometimes around 10 meters of diameter), in a very water saturated soil matrix. It would present many difficulties for construction, portal slope stability and even for the initial excavation cycles of the tunnel, since the blasted rock boulders could destabilize large portions of saturated soil. The geology team alerted the geometry team and the project coordinator, and the highway alignment was changed to a better localized place.

3.3 *T401/302*

T401/302 tunnel had one of the major changes in design of the Contornos project: in the beginning of the project, two tunnels were predicted. T302 southern portal and the nearby T401 northern portal were both located in a very steep hillside, and densely vegetated area of Serra do

Mar. Between the two portals, one cut (about 60 meters high), one embankment and a bridge were foreseen. The portals were located at about 80 meters above sea level.

When conducting debris flow vulnerability studies for the entire highway, the geology team noticed a high susceptibility to debris flow events in the hydrographical basin crossed by the sector between the two described tunnel portals (Cunha *et al*. 2018). Debris flow events are widely known by geologists that work in the Serra do Mar region (Gramani & Kanji, 2001), and thus, it was expected, from the beginning of the project that some sites could be susceptible. It was found that a debris flow event could damage the highway structures, mainly the bridge pillars, located inside a valley.

The debris flow susceptibility, combined with other factors, like construction difficulties to access and to execute the construction itself, vegetal suppression needed to reach the construction site, erosion and mass movements vulnerability of the construction paths and the highway once finished, led to a change in the highway alignment.

The geology and geometry team acted together to push the new alignment inside the terrain as much as it could be done, joining the two previous tunnels into one, and placing them in a area with a reasonable overburden. One high cut, one embankment, one bridge, two tunnel portals and numerous construction activities in a problematic area were avoided, resulting in a safer highway for decades to come.

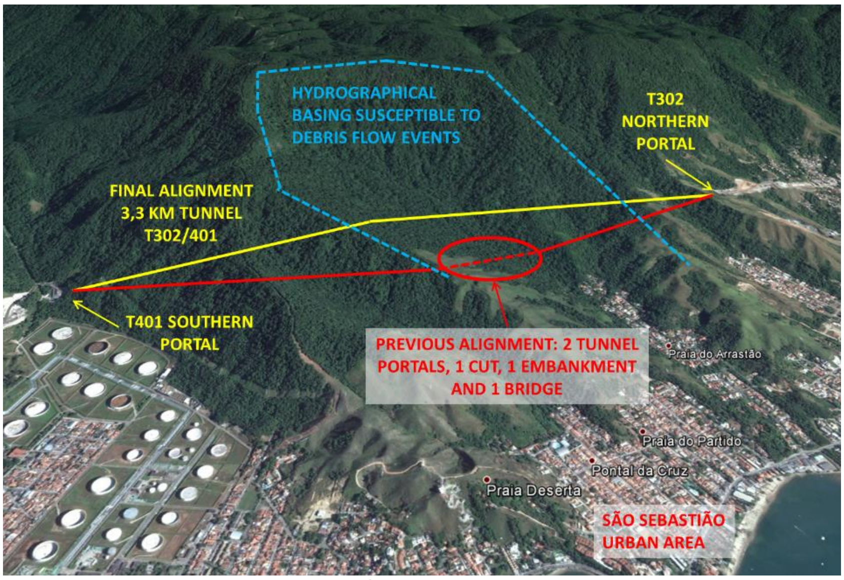

Figure 7. T302/401 previous and final design setting.

4 CONSTRUCTION AND EXCAVATION

Excavation for the tunnels took about 4 years, and it is mostly finished. Other works are not finished yet, like electrical and automation works. Here, we present some main features and challenges during excavation phase.

4.1 *Main features*

In general, excavation works for the longer tunnels had a faster rate than the shorter ones, due to better conditions of unweathered rock. The shorter tunnels (T101, T102 and T402) had to deal with constant changes in support and excavation classes, due to changes in rock or residual soil condition and the highly heterogeneous weathering profile of the region. It was common to find weathered, but resistant rock and residual, mature soil in the same cross section for the shorter tunnels, resulting in multiple drift need for excavation support, but combined with blasting for the rock portions. This led to longer excavation cycles, since the long times of support measures were combined with the long times for blasting and cleaning.

In the longer tunnels, water and intensely sheared and fractured zones were the major factor of concern. They were not factors that made excavation come to a halt, but required caution from the design and construction team when approaching the best way to deal with some sectors. Since overbreaks caused by the rock foliation were common, the geologists in the excavation front had to be aware of the design methods available to correct the excavation section.

Another occurrence in the longer tunnels were rockbursts/stress releases causing rock boulders to detach from the tunnel face, ceiling and walls, in the time span between installation of supports and application of shotcrete. These occurrences happened in tunnel sectors with a high quality rock, with no fractures.

Although, punctual and rare, these occurrences caused the excavation works to stop for a while before the design team, together with the client and construction team came to an agreement of how to deal with it. The measures included using a RMR class below the one mapped on tunnel face, and installation of all supports (shotcrete, rockbolts, metallic wire and lining) before beginning the drilling for blasting. This occurrences of rockbursts/stress releases denote the geological history of a region has to be studied, so that we can understand the tectonic stress in place.

T302/401 also had an unique occurrence of a mafic rock (metagabbro) with swelling behavior, due to swelling clay mineral, in a sector of the tunnel 150 meters below surface. This behavior is not described in the geological maps or technical bibliography, since the rock disintegrates in the presence of water, and could not be detected in usual methods of investigation, like boreholes. The result was a stop in excavation works for almost 3 months, before the behavior of the rock and the best way to deal with it was understood. Several laboratory analysis and field investigations (like horizontal rotary drilling, starting from the excavation face) were carried on and the tunnel design team had to create a new support and excavation class to deal with the new material, and several design documents were elaborated to base the new construction method adopted. The authors of this paper will present a future work describing this peculiar rock.

5 RESULTS AND CONCLUSION

Besides usual NATM adjustments and modifications, like exchange of one excavation class for another in some stretches, construction phase had to deal with problems like falling rock boulders due to rockburst/stress release, swelling behavior and occurrences of water infiltration with high flow rate.

All these problems were possible to overcome, with varied degrees of time and planning needed, due to the nature of the NATM philosophy of allowing modifications to take place. From small changes in the excavation distance step to complete redesigns of tunnel lining and support, each problem required different approaches, like additional instrumentation, additional investigation, decrease or increase of time between excavation steps, among many others. The tunnels in this project proved that NATM is a very effective way of excavation in a context like the one presented here. One could look at the total excavation length alone (more than 10 km) and suggest the use of mechanical methods. But, difficulties to access portal sites, varied types of materials, varied sizes of excavation sections and distance between tunnels pointed to the NATM method.

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